THE UNIVERSITY OF MICHIGAN
ELECTRO-OPTICAL SCIENCES LABORATORY

NsG-698/23-05-35
Semi-Annual Status Report #3
June 1, 1965 - November 30, 1965

NOVEL TECHNIQUES FOR RULING IMPROVED LARGE DIFFRACTION GRATINGS

"This report, not necessarily in final scientific form, is intended for the internal management uses of the National Aeronautics and Space Administration".

Project Director

George W. Stroke

George W. Stroke

November 30, 1965

SUMMARY

We wish at this time to stress one most important advance achieved during this period in our work to attain newly powerful high-resolution gratings. In only 9 months time the 32 inch x 20 inch grating ruling engine, designed by us according to our Report #1 was completed and delivered on 30 August 1965 by the Moore Special Tool Company, at a minimal cost of only $32,050, for the engine as shown in our Fig. 1.

As a result of exhaustive tests which we have carried out since September 1, 1965, we are now in a position to report a complete success in all of the motions of the two carriages over their 32 inch traverse. With the teflon bearings which we designed-- in contrast with previously used and notoriously unreliable oil bearings-- we have achieved

1. Perfect uniformity in translation motion (in the direction of the x-axis) in the 10^{-7} inch range, without any stick-slip (See Fig. 2).
2. Absence of yaw (rotation) about a z-axis (normal to the grating plane), the tolerable rotation being inferior to a smoothly varying .43 sec on the main carriage and to 1.23 sec on the support carriage.
3. Absence of pitch (about a y-axis in the grating plane, normal to the x-axis translation) inferior to a smoothly varying $\pm.5$ fringe on the main carriage and $\pm.75$ fringe on the support carriage (in a 5 inch lever arm).

These important and certainly nottrivial results (in comparison with for instance the status of delivery of previous comparable engines using hydraulic lubrication) may be taken as having gained perhaps one to two years in advancing the completion of this research, notably because of the simplification in the diamond control system and carriage design which may now be undertaken, on the basis of these accomplishments.

DETAILED REPORT

1. DOUBLE-SCREW ENGINE CARRIAGE TRANSLATION MEASUREMENTS

Fig. 1 shows a photograph of the new engine, constructed according to our design given in Report #1 (Fig. 1). Apart from outstanding workmanship, and the utmost mechanical precision essential, and used, in completing this engine, the single most important feature is the use of .007 inch thick 'rulon' (teflon) bearings, cemented onto the double-vee meehanite bearings with "Garlock 20" epoxy adhesive, and scraped in the best mechanical fashion for perfect fit. (The immediate success in the rulon bearings, in spite of some serious questions raised regarding the wisdom of using teflon bearings, has no doubt also resulted from the long experience of us in astronomical instrument design (O.C.M.) and in ruling engine work (G.W.S., F.D., P.W.), and notably from out work (G.W.S. and F.D.) on the M.I.T. ruling engine with Dean G. R. Harrison as well as from the work of one of us (G.W.S) on the engines at the Jarrell-Ash Company in Newtonville, Mass. and on the engine at the Jobin et Yvon Company, in Paris). Fig. 2. shows the regularity of motion achieved at a speed of 1/3 fringe (i.e. 3164Å, that is about 3 x 10^{-6} inch) per second with the teflon bearing carriages. (The more widely spaced fringe signal was obtained with our "synthesized fringe" interferometer, described in paragraph 1 and Fig. 1 and Fig. 2 of our Report #2).

2. CARRIAGE ROTATION MEASUREMENTS

These were carried out with the aid of the "alignment interferometer" previously described by G. W. Stroke (J. Opt. Soc. Am. 51, 1340-1341, 1961). (Copy enclosed). We recall that this interferometer remains as perhaps the only simple interferometric tool for immediate and rapid measurement and assessment of carriage rotation motions in the interferometric domain. Basically, the "alignment interferometer" consists simply of a "folded" Michelson Twyman-Green Interferometer, in which both mirrors are supported on the moving carriage, and move essentially at the same rate away from a fixed beam splitter, except for small rotations, which manifest themselves as small fringe shifts. Because of the simultaneous increase of the optical path difference in both arms of the interferometer, very rapid measurement of rotations over very long traverses are possible. For example, once installed, a single measurement over the entire 32-inch traverse may take less than five minutes. In the case of our new engine, we have found our carriages to be perfectly straight within uniform smooth small rotations inferior to 43 seconds of arc on the main carriage and 1.23 seconds of arc on the support carriage. These results are quite superior to previously designed ruling engines, and should permit considerable simplification in the interferometric servo-control requirements and indeed the mechanical design of our moving diamond carriage system.

3. CARRIAGE PITCH MEASUREMENTS

A vertical rotation interferometer (shown in Fig. 4.) has also permitted us to measure the pitch of the two carriages and to verify the excellence achieved according to our teflon-bearing engine design. We have found our main carriage to be perfectly straight within a single uniform smooth small oscillator along the entire 32-inch traverse inferior to 2 seconds of arc, and inferior to $\pm$ 3 seconds of arc, at a medium height of some 5 to 6 inches above the grating plane. (The pitch in the carriage and grating planes are proportionally still smaller, of course).

4. DIAMOND-CARRIAGE SYSTEM DESIGN

The above results for the carriages supporting the transversal diamond-carriage system (see Fig. 1 of our Report #1) now permit to embark on the detailed design of this system. Progress and further experimental results regarding this part of our research will be given in our next report. Unusual requirements for excellence in instrument making workmanship and ver direct supervision continue to be essential in the pursuit of this work.

5. HANDBUCH DER PHYSIK ARTICLE ON "DIFFRACTION GRATINGS"

The 225 printed-page article (plus figures) by Professor G. W. Stroke is now in the final printing and proof-correction stage. The enclosed copies of the proof-pages 187a to 187y dealing with Section 88. Some of the modern ruling engines, is enclosed as a private communication, and part of this report.

6. ARTICLE ON A "SOLUTION OF THE NON-HOMOGENEOUS HELMHOLTZ EQUATION FOR OPTICAL GRATINGS WITH METALLIC AND DIELECTRIC BOUNDARIES

The article by R. C. McClellan and G. W. Stroke has now been accepted for publication in the Journal of Mathematics and Physics (published by the M.I.T. Technology Press, Cambridge, Massachusetts. The results of this rigorous electromagnetic boundary solution for gratings should set the stage for new improvements of grating efficiency, with results quite comparable to those pertaining to the increase in grating size.

PERSONNEL

Dr. Orren C. Mohler	Director No charge to project
Dr. George W. Stroke	Project director and principal investigator
Frank Denton	Grating Ruling Engineer
Paul Peters	Graduate Research Engineer
Paul Weyrich	Instrument Maker part time
H. R. Roemer	Physics Shop Supervisor part time
Rolf McClellan	Graduate Assistant part time
Nancy Pruitt	Administrative Assistant part time

Yours very truly

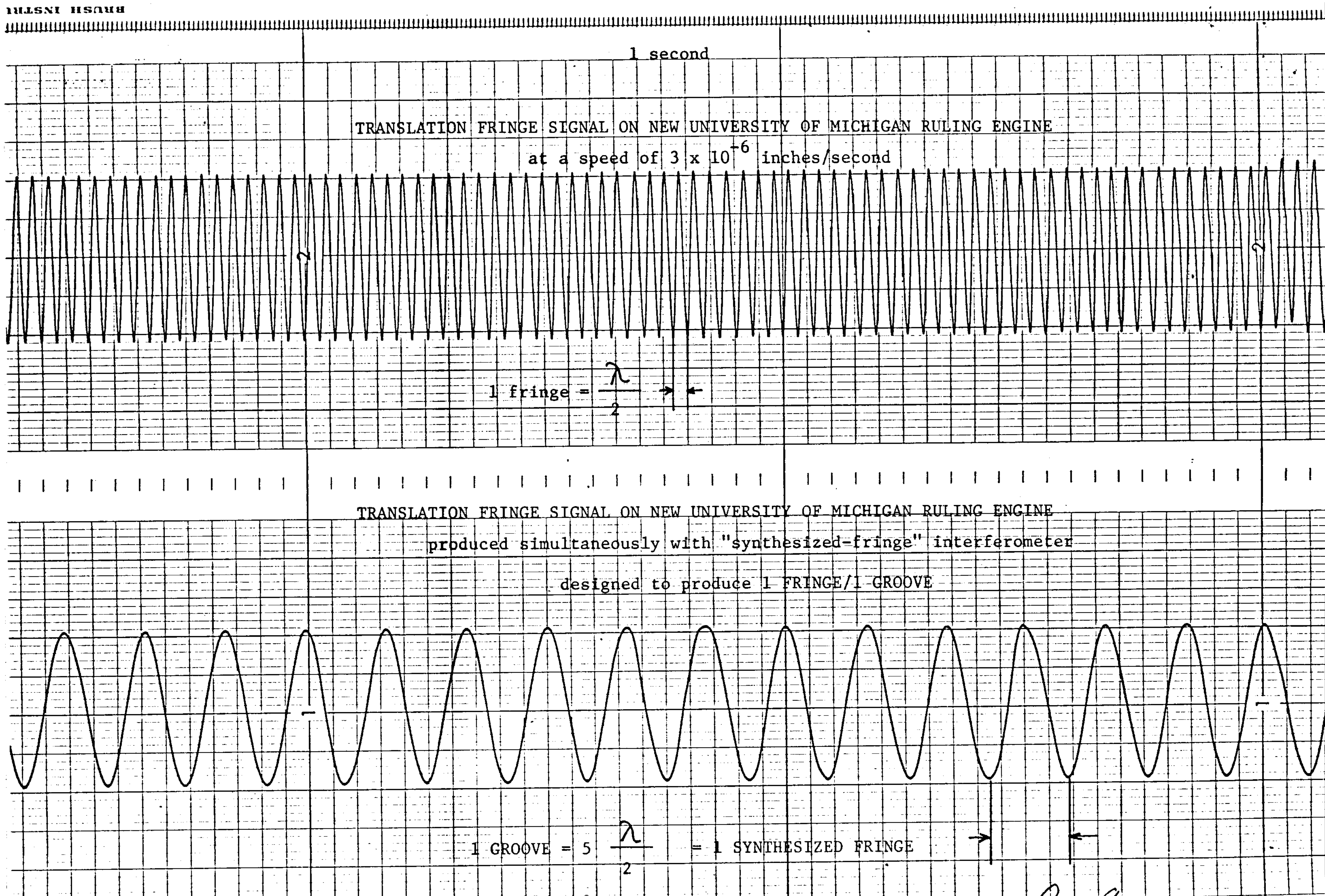
George W. Stroke

George W. Stroke
Principal Investigator

Distribution List

National Aeronautics and Space Administration (25)
Dr. Henry J. Smith (2)

FIG. 1 NSG-698/23-05-35 Report #3 30 Nov. 65 [signature]



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GW Stroke

FIG. 2

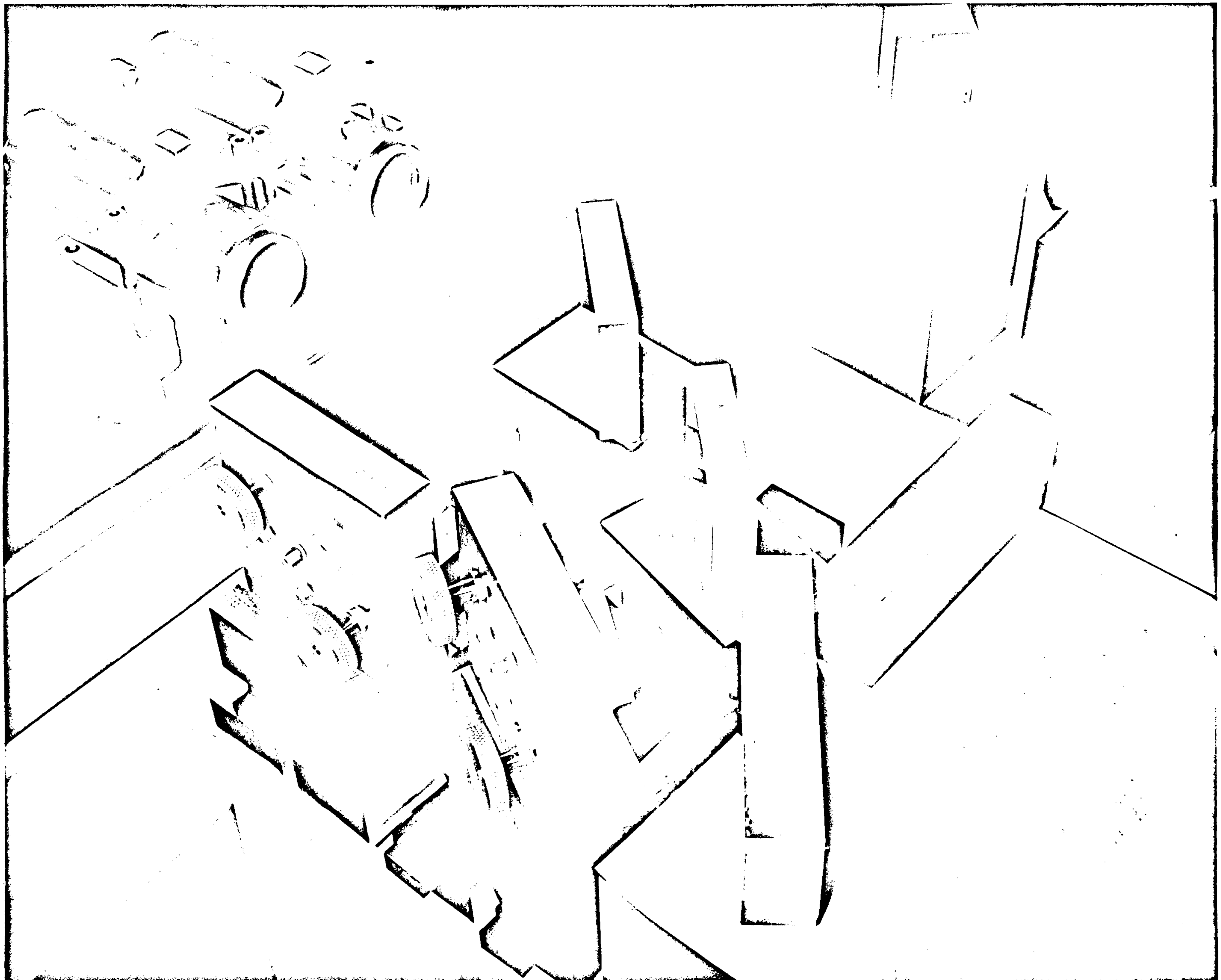

FIG. 3 NSG-698/23-05-35 Report #4 30 Nov. 65 [illegible signature]

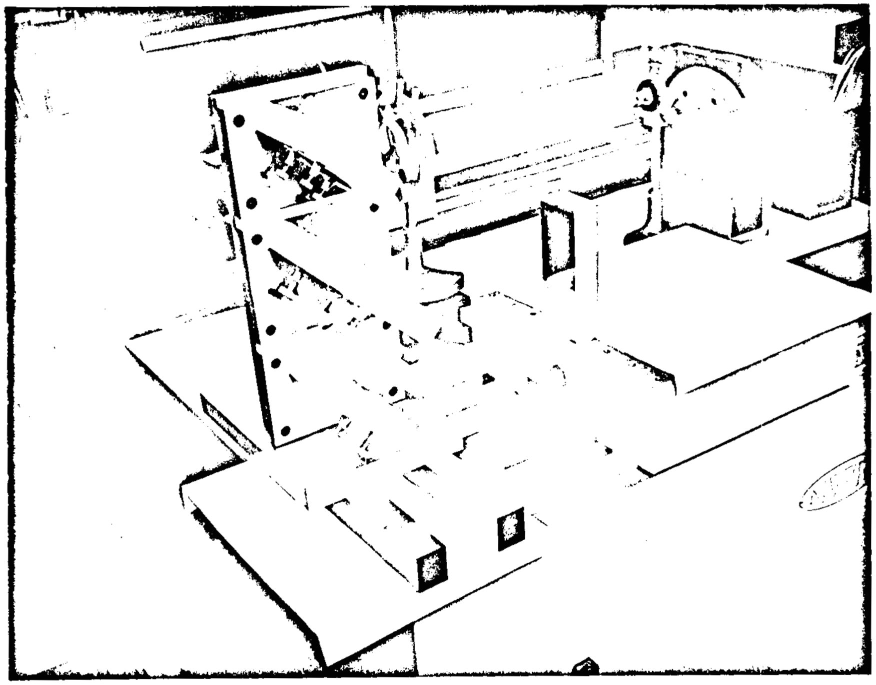

FIG. 4. NsG-698/23-05-35 Report #4 30 Nov. 65

Reprinted from JOURNAL OF THE OPTICAL SOCIETY OF AMERICA, Vol. 51, No. 12, 1340–1341, December, 1961
Printed in U. S. A.

An Alignment Interferometer for Precision Straightness-Measurements and Control Even of Rapidly Moving Carriages

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*Department of Electrical Engineering and Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge 39, Massachusetts**†

(Received July 17, 1961)

A new, easily adjusted and very stable interferometer, defining a semistatic fringe field by reflection on two mirrors, has permitted a simple solution to the problem of rapid and accurate alignment of moving carriages, of fixed reference beams, and of carriage-ways in the interferometric domain. Precisions in the 0.1 sec of arc range are easily obtained in visual work in rotations up to minutes of arc, *without* the usual limitations of slow fringe counting and of loss of fringe contrast at large path differences in particular. In fact, the fringe contrast is independent of the distance *from* the reference support to the moving mirrors in this interferometer, and permits measurements and alignments over traverses and distances of many feet if required. Precisions in the 0.01 sec of arc range and better can be obtained with the help of electronic location of interference fringes. Experiments with carriages moving at rates up to 1-foot/sec and over distances of the order of 1½ ft have demonstrated the versatility of the alignment interferometer in various applications, in particular in the alignment of ways on a velocity-of-light apparatus and on ruling engines.

AS shown in Fig. 1, the alignment interferometer consists of a folded two-beam arrangement with one beam-splitting and three reflecting mirrors placed on a fixed support so as to have almost the same path lengths SAD and $SBCD'$ from the beam-splitter to a "moving" mirror (DD') in the two arms of the interferometer. As long as the moving mirror (DD') moves in the y direction without any rotation about the z axis, the path lengths in both arms SAD and $SBCD'$ increase by the same amount and no fringe shift is observed in the interferometer. Any rotation about the z axis changes the path difference (SAD–$SBCD'$) and results in a fringe shift observable at R.

The mirrors are so adjusted as to obtain an equal-inclination ring system[1] in the focal plane of the lens $L2$, which permits both visual and photoelectric detection with an unvarying fringe contrast, independently of the y distance of the "moving" mirror: the path lengths in both arms are indeed seen to vary by the same amount, except, of course, for the small change which is, precisely, a measure of the rotation about the z axis.

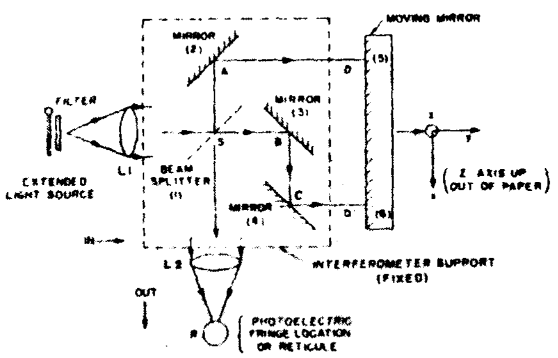

FIG. 1. Alignment interferometer.

One notes that the distances SA, SB, and BC would have had to be exactly the same if a "zero" path difference (SAD–$SBCD'$) had been desired. In fact, a suitable small path difference—of the order of a few millimeters—and appropriate mirror adjustments result in the desired appearance of the equal-inclination ring system in R. If the x axis is chosen to coincide with DD', then the four interferometer mirrors are set approximately at 45° to this axis. The adjustments are not critical at all, of course; the only requirement is the coincidence of the outgoing beams reflected from D and D'. One can easily see by symmetry that the interferometer is sensitive only to rotations about the z axis, and insensitive to rotations about the x axis as well as to translations in the y direction. A very rapid motion, of the order of 1 ft/sec, has been found to be perfectly tolerable in a straightness measurement over a 1-ft traverse.

An extended light source is used for both visual and photoelectric detection of shifts in the ring system formed in R, when displacements of a given ring are measured. In visual measurements, a reticule and eyepiece used in R have permitted easy measurement of fringe shifts of the order of 0.1 fringe (in the green, at 5461A) which corresponds to about 0.02 sec of arc on a 10-in. lever arm DD'.[2] For photoelectric detection, the system for "electronic location of interference fringes" previously described by J. Peters and G. W. Stroke[3] is particularly suited: we have already reported a sensi-

* Part of this work was carried out in the Spectroscopy Laboratory of the Massachusetts Institute of Technology.
† This work was supported in part by the U. S. Army Signal Corps, the Air Force Office of Scientific Research and the Office of Naval Research, and in part by funds received under contract with the Geophysics Research Directorate, Air Force Cambridge Research Center, Air Research and Development Command.
[1] G. W. Stroke, J. Opt. Soc. Am. 47, 1097 (1957); 48, 276 (1958).

[2] One inch equals approximately 100 000 fringes at 5461 A (green mercury line) and 1 sec of arc equals approximately 5/10⁶ radians. Thus 0.1 fringe in a 10-in. lever arm corresponds to about 1/10⁷ radians (or 1/50 sec of arc).
[3] J. Peters and G. W. Stroke, J. Opt. Soc. Am. 43, 668 (1953); 43, 1231 (1953).

tivity of the order of 1/400 fringe, which corresponds to 0.0005 sec of arc on the 10-in. lever arm.[4]

The rotation-measuring fringe-shift observed in the R plane follows well-known and simple laws, identical to those characteristic of the position of Fabry-Perot rings[5]: it can be easily calibrated for any particular case by simply referring the fringe-shifts to a scale determined by the diameters of two successive rings. In particular, when one ring takes the place of another, the difference between the distances SAD and $SBCD'$ has simply changed by one fringe, and similarly for an integral number of fringes within the range in which the diameters of the rings do not appreciably change with an integral change in order of interference $(SAD-SBCD')/\lambda$. No calculation is required in null alignments or adjustments for which the interferometer is most ideally suited.[6]

The alignment interferometer has been applied in particular to the alignment of the grating-carriage ways on the M. I. T. ruling engine: an over-all straightness of about one fringe in a 10-in. arm and over a 10-in. traverse was obtained in less than 1 hr and independently verified with the help of the "two-interferometer" rotation-measuring system which we had previously designed for this purpose.[7-9]

The alignment interferometer is also being applied to the measurement of the straightness of motion of the moving piston in the M. I. T. microwave-cavity-resonance, velocity-of-light apparatus[10] of which the design principles have been described by G. W. Stroke and J. R. Zacharias.[11]

When control over very long traverses is desired, a suitably reduced atmospheric pressure will reduce any possible turbulence in the interferometer arms. In our experience so far, no such difficulties were encountered. Straightness of travel about both the z axis and the x axis, normal to the y direction of motion, can be maintained and measured with the help of two alignment interferometers and two "moving-mirror" systems placed at right angles to each other. It is clear that the alignment interferometer can be used for accurate alignment, with respect to a suitable permanently adjusted "interferometer support" (see Fig. 1), of a mechanical beam or other apparatus carrying the (5) + (6) mirror system. It is also clear that the mirrors (5) and (6) do not have to be a part of the same mirror at all. In fact the light beams AD and CD' do not even have to be parallel, and the mirrors (5) and (6) may be deliberately set to move at some angle to each other in certain applications.

ACKNOWLEDGMENTS

The author wishes to thank Dean G. R. Harrison for stimulating this research by valuable discussion in stating the advisability of a "zero-path" interferometer for the control of moving grating carriages. He also wishes to thank the Spectroscopy Laboratory for the use of their laboratory facilities and the Physics Department Shop, under the direction of Joe V. Yena, for effective mechanical assistance in assembling the interferometers.

[4] It is clear that very large rotations up to minutes of arc can be measured with this interferometer by using somewhat shorter lever arms (with a 4 in. lever arm, a passage of 120 fringes through the field can be easily read and gives a total angle of about 1 min of arc): for this purpose, it may also sometimes be of advantage to restrict the aperture widths of the mirrors (5) and (6) in the x direction and use apertures in the form of "slits" with their length parallel to the z axis.[1]

[5] P. Jacquinot, Repts. on Progr. in Phys. 23, 267 (1960).

[6] The "equal inclination" ring fringe system formed by this interferometer, as a result of the path-difference deliberately introduced between the two beams, gives it an essential advantage in fringe position reading accuracy over a "zero-path" difference interferometer using a wedge between the beams and producing an "equal thickness" line-fringe system, such as the alignment interferometer described in U. S. Patent No. 2,880,644 (April 7, 1959) by E. M. Brockway and D. R. Herriott: that interferometer applies a Kösters double image prism assembly for both beam splitting and the attainment of the necessary "lever arm" and angular rotation sensitivity, and is thus generally also further limited by the available prism dimensions to only much smaller sensitivity values than the ones considered in the alignment interferometers using mirrors and an equal-inclination ring system discussed in the present work.

[7] G. R. Harrison and G. W. Stroke, J. Opt. Soc. Am. 45, 112 (1955); 50, 1153 (1960).

[8] G. R. Harrison, N. Sturgis, S. C. Baker, and G. W. Stroke, J. Opt. Soc. Am. 47, 15 (1957).

[9] A straightness of better than 0.02 fringes across the interferometer arm is obtained in this engine with the help of the "two-interferometer" servocontrol system which operates from the difference between the two fringe signals produced by the motion of two portions of a long mirror, moving at the rate of about 2.5 fringes/sec. A fringe rate of about 40 fringes/sec, usable for measuring purposes, would require about 23 hr for a single straightness reading over a 10 in. traverse with the "two-interferometer" system, while this reading can now be obtained in only a few minutes with the new alignment interferometer described here.

[10] J. R. Zacharias, G. R. Harrison, G. W. Stroke, S. J. Mason, and C. L. Searle, Mass. Inst. Technol., Research Lab. Electronics, Quart. Progr. Rept., (January 15, 1956), p. 68.

[11] G. W. Stroke and J. R. Zacharias, Mass. Inst. Technol. Research Lab. Electronics, Quart. Progr. Rept. (October 15, 1958), p. 69.

From article 'DIFFRACTION GRATINGS' G. W. STROKE
in Handbuch der Physik, Vol.29, edited by S.Flügge
(Springer Verlag, Berlin and Heidelberg, in print).

Pages 187a to 187y

[redacted] stirrers and appropriate shields to avoid lag in the sensing and suppress temperature oscillations. A period of 12 to 18 hours is usually required to raise the engine and oil to operating conditions."

The control of the M.I.T. engine room is maintained to about $\pm 2/100°$ C at the point of control, and the air is constantly gently stirred by slowly rotating, and moving, fans. Control-air is blown into the engine room from an outer room, at a point where that room is controlled to about $\pm 0.15°$ C. And finally, the outer room is itself controlled with air from the main laboratory, maintained to about $\pm 0.5°$ C by means of the air-conditioning system previously described in 1932 by K. T. Compton (loc. cit. [38]).

Babcock and Babcock (loc. cit. [9], p. 780) report that the Mount Wilson machine

"... is housed in a double-walled, aluminum-foil-lined enclosure with windows and removable panels. A constant-speed fan circulates air within the enclosure and a thermostat holds the temperature during ruling to $24.0 \pm 0.005°$ C. The temperature of the outer room is controlled to $0.1°$ C."

88. Some of the modern ruling engines. α) *The new Johns Hopkins Ruling Engine.* A first description of this engine was given by John Strong in 1951 (loc. cit. [8]) and additional details on its performance in 1960 (loc. cit. [6]). 6-inch gratings are being regularly ruled on this engine.

A schematic diagram of the Strong engine is shown in Fig. 137. It is to be compared to the diagram of the Rowland engine shown in Fig. 138.

In Strong's engine, the diamond carriage is advanced with the help of the two counter-rotating screws, while the ruling of the groove is accomplished by moving the grating blank under the diamond carriage, after it has been stopped. The purpose of the two counter-rotating screws is to help in averaging out errors inherent in any one of the screws.

As reported by John Strong in 1960 (loc. cit. [6]): "The new engine was successful, and three replicas of that engine have been made."

Complete details on the design, construction and experiments with his new engine are given by Strong in his 1951 article (loc. cit. [8]). A photograph of the engine is shown in Fig. [redacted], and some details on the squared lapping nut used to obtain a helix concentric with the bearings is shown in Fig. [redacted].

John Strong's engine undoubtedly represents the finest and most sophisticated example of "built-in" perfection successfully achievable in a ruling engine. As described by Strong:

Design principles.

"A principle which guided Rowland in his original design was 'that no workmanship is perfect; the design must make up for its imperfections.'[38] Rowland's implied meaning has afforded a basis for many of my own innovations.

A subsidiary principle has had considerable influence in my design — *the principle of overconstraint and elastic averaging*. This principle contrasts with the principle of kinematical design[39]-instruments of the very highest precision are not attainable after the teachings of the latter.

After my principle of overconstraint with elastic averaging, one uses a multiplicity of small contacting areas, each provided with enough elasticity to accommodate variable oil films, foreign matter, inhomogeneity of elasticity of the constrained member, lack of truth in the generated surface of the constrained member, and wear. Unavoidable errors at any one of these many areas will be elastically averaged to give a far more precise resultant location of a moving part than one would get from constructions designed after the kinematical principle which this type of construction contravenes. Varied applications are described later."[8]

[38] H. A. Rowland: The Screw. Encyclopaedia Brittanica XI.
[39] J. Strong: Procedures in Experimental Physics, p. 585. New York: Prentice-Hall, Inc. 1938.

Handb. der Physik, Bd. 29 Stroke Springer-Verlag, Heidelberg
1. Korr. Univ.-Druckerei H. Stürtz AG., Würzburg
29. 12. 1965 Mskr. 433—482a Fahnen a—y

On lapping.

"The new design requires great precision of construction. The main difficulty of precision metal constructions of such members as a lead screw lies in the operations of lapping soft metals, which materials alone are sufficiently stable mechanically and free from aging. It is not inappropriate therefore to say a few words about the lapping procedure. The lapping operation bears the same relation to precise mechanical constructions that "figuring" with a pitch polishing lap bears to precise optical work. Although metal surfaces may be scratched or grooved (owing to generation being of the cylindrical rather than the spherical type) and although they may be less true locally than polished, hard surfaces, elastic averaging gives such lapped metal surfaces a precision of performance comparable with the truth of optical surfaces." [8]

Further details on the lapping and other procedures used to achieve truly unique mechanical precision are given in the original paper. As noted by STRONG (loc. cit. [8]) in that paper:

"The satisfactory performance of the new engine is the result of the excellence of its components, and especially to PERRY'S[40] prompt assay of their operating characteristics, in ensemble, and his skillful and sure adjustments." [8]

β) The Mount Wilson observatory engine (before control). BABCOCK and BABCOCK (loc. cit. [9]) reported in 1951:

"Within the past three years, about 20 blazed plane gratings having a groove length $5\frac{3}{8}$ inches and a width of $7\frac{3}{4}$ inches have been ruled here."

These gratings were of high quality "in all respects" and could be produced "with fair regularity". A general view of the engine, described as the *B* engine is shown in Fig. 139. As described by BABCOCK and BABCOCK in 1951 (loc. cit. [9]):

"The present satisfactory performance of the "B" machine rests, in our opinion, upon these considerations:

(1) the geometry of the modified design which tends to eliminate the troublesome errors encountered in most earlier machines;

(2) the use of a graphite thrust bearing for the screw;

(3) the use of stable, stress-free materials for critical parts, and surface-hardened Nitralloy steel for the ways, in combination with graphite sliders;

(4) improved technique in the production and use of ruling diamonds;

(5) the superlative tool-room skill of E. D. PRALL, who made or finished nearly all the critical parts and who made important contributions to the design as well." [9]

Some of the construction details, as given in the original paper (loc. cit. [9]) are as follows:

Design.

"The main frame of the machine is a symmetrical, compact, deeply-webbed iron-nickel casting, resting upon three thermally-insulated supports on a concrete pier. This casting supports the ways of the grating carriage, the screw with its spacing gear, and the crossway of the diamond carriage. A separate casting on a separate foundation carries the crankshaft with its fly-whell and eccentrics, the spacing cam, and the cross-head; thus possible sources of vibration are isolated from the critical parts and possible objectionable deformation through settling or warping is minimized." [9]

Screw.

"The screw has a threaded length of 20 inches and a diameter of $2\frac{1}{4}$ inches; the pitch is $1\frac{1}{2}$ mm. It was made from a selected bar of No. 30 Bethlehem Machinery Steel (0.41 percent carbon) which after roughing was carefully annealed in a vertical position. The thread angle is 52°, the thread root is relieved by a deeper burnished groove. Great care was taken in cutting the thread to make it as nearly perfect as possible before lapping was commenced. Lapping, which was completed in 145 hours distributed over five months, was carried out with the screw in a vertical position and with the two halves of the lapping nut counter-weighted. The halves of two long lapping nuts were used in all possible combinations; three short nuts were used for local work and for testing. The ends of the screw are fitted with hardened Nitralloy steel sleeves, pressed on and pinned; as lapping of these journals progressed, they were tested with an overhanging optical lever supported by a long nut. The screw was

[40] WILBUR PERRY: The Johns Hopkins University.

tested for straightness and uniformity with the Fabry-Perot interferometer as described by ANDERSON[41] until no errors could be detected. Various other components of the machine were likewise tested with the Michelson interferometer." [9]

Bearings.

"The bearings in which the screw turns are of Meehanite (cast iron) and are about two inches in length. They are not self-aligning. Each is in three parts, the cap being split parallel to the screw. The two parts of the cap are doweled and screwed to the lower part of the bearing. Contact area is limited to three 30° arcs spaced at 120°, one being at the bottom. The bearings were lapped on a dummy screw." [9]

Nut.

"The nut is eight inches in length and is divided into halves, the dividing plane being vertical. It was prepared by centrifugally casting a hard nickel babbitt into a steel shell having 12 internal dove-tail grooves. Excess babbitt was then turned out to leave 12 segments, after which the nut was sawed in half and threaded. The nut is assembled with a demountable spring and pivot-pointed screws at each end. Rotation is prevented by two eight-inch fins bearing on a straight-edge below the screw. The thrust of the two halves of the nut is transmitted by two two-inch, ball-ended push rods to the opposite sides of an equalizing collar that is attached to the grating carriage by two short studs, through bending, permit a slight rotation of the collar about a vertical axis. These push-rods, which fit into hardened steel cones, eliminate any concern about the sag of the screw or about lack of parallelism between the screw and the ways, also they would minimize any periodic error due to lack of straightness of the screw, though no curvature or "drunkeness" has been detected. The nut is lubricated with Spindle Oil No. 11 (E. F. Houghton and Company); its fit is so good that as shown by cross-ruling tests, oil films as well as strains are equalized within a few cycles of operation after the machine is started." [9]

End thrust.

"On the end of the screw opposite the spacing gear is mounted a diamond, cast in phosphor bronze. The diamond was figured flat to $\frac{1}{10}$ wave and adjusted, by a reflection test, to be perpendicular to the axis of the screw to a small fraction of a second of arc[41]. For years we employed a hard metal sphere as the fixed part of the bearing, but all too often this broke down as the result of chipping or scoring. This difficulty was solved in March, 1948, when we introduced a graphite compound as the fixed part of the bearing. A short, firmly supported, coaxial stub of this material* about 1.5 mm in diameter forms an excellent bearing surface for the diamond. The graphite is relieved by a very small hole at the center. We find that a slightly pitted surface, formed by honing on ground glass, performs better than a completely smooth surface. No self-aligning feature is needed. In our machine the thrust load is about seven pounds." [9]

Spacing mechanism.

"The principle of this mechanism, which was taken over from the "A" machine, is due to JACOMINI. A thrust-pin, driven by a crank, moves through a tapered helical groove in a cylindrical cam once each cycle, causing the cam to rotate through one turn. The thrust-pin is retracted from the cam on the return stroke by a wedge device that is activated by an eccentric with a lost-motion connecting rod. Through three spur gears, the intermittent rotation of the cam is transmitted to a Nitralloy worm which is in mesh with the 900-tooth spacing gear attached to the end of the main screw. The mechanism is smooth in operation and has the great advantage that by a simple change of gears a wide variety of grating spacings is available. Gears on hand permit spacing from 200 to 1800 grooves per mm, but the greater part of our ruling is done at either 400 or 600 per mm. Wear of the hard steel worm is negligible, and, as Anderson showed years ago, extreme precision in the spacing gear is not required[41]. Our spacing gear was carefully lapped, however, both against a single lapping worm and against three co-ordinated worms spaced at 120°. As used for some years, this system gave what is often considered an acceptably low periodic error, such that the intensity of the first Rowland ghosts in the ruled gratings was about 0.001 of the parent line in the first-order spectrum. In 1949 ghost intensity was further reduced by a factor of 25, however, by the addition of the relatively simple period compensator shown. The spacing worm has a small end-thrust bearing of its own, which is mounted on a fine-pitch screw. A lever, attached to this screw,

[41] J. A. ANDERSON: The manufacture and testing of diffraction gratings. Glazebrook's Dictionary of Applied Physics 4, 30–41 (1923).

* Graphitar, a product of the U.S. Graphite Company, Saginaw, Michigan.

and bearing on the flat surface of a large disk mounted obliquely on the hub of the main spacing gear, generates a very small oscillatory longitudinal displacement of the spacing worm. This oscillatory correcting motion has a period equal to the period of rotation of the main screw, its amplitude and phasing were adjusted following the study of cross rulings. The mechanical advantage is such that the throw of the cam is reduced by a factor of about one million in its effect on the correction of the position of the grating carriage, yet the correction is "rigid" and readily controllable. In adjusting the machine to rule gratings with Rowland ghost intensity less than 0.00004 in the first order, the amplitude of the permitted periodic error in groove spacing is held to less than 2×10^{-7} inch." [9]

Additional details are given by BABCOCK and BABCOCK[9] concerning the grating carriage and the diamond carriage:

Diamond carriage.

"In his article on the ruling engine, Anderson properly rated the diamond carriage, or ruling carriage, as the part of the machine presenting the greatest difficulty[41]. The demands are truly enormous when it is considered that in ruling a single grating the diamond should move in the same straight line upwards of 100000 times without lateral deviations of more than a fraction of a micro-inch; that the carriage must reverse its direction of motion at each end of the stroke, and that it is supported and guided by ways subject to waer and influenced by oil films. It has been our experience that while it is not too difficult to obtain satisfactory performance with groove lengths up to three or four inches, the errors are likely to be much more troublesome when longer grooves are ruled. The statement is sometimes found that since the errors of position of the diamond carriage are usually random in nature, they are of little consequence compared to periodic errors. But as Anderson pointed out, such random errors lead to a flare of flase light centered on each emission line in the spectrum (we have employed the term 'local scattering' for this). This local scattering broadens strong emission lines and, in an absorption spectrum, is an insidious source of filling in of absorption profiles.

A number of ruling engines, including ROWLAND's have employed a four-footed diamond carriage moving on two parallel ways; usually the ways are flat-topped, with the sides vertical or nearly so. The weight of the carriage is taken by the flat top, while in theory the critical lateral definition is supplied entirely by the steep sides (spring loaded in opposite directions at the two ends). We have introduced three modifications in the design of the diamond carriage. The first, in 1934, was to support and guide the bridge type carriage by a divided monorail, the ruling diamond working in a gap on the axis of this rail. Stability of the carriage about this horizontal axis is provided by an outrigger at one end of the carriage, riding on an ancillary parallel rail. The advantages are that any rocking of the carriage will not displace the diamond from its proper path, that the carriage is lighter, and that fitting it to a single rail is far simpler than fitting it to two. In 1950 we replaced the flattopped monorail by a cylindrical rail, slightly over one inch in diameter. This rail is of NITRALLOY; it was first centerlessground, then lapped in a lathe to a high degree of straightness and uniformity by STRONG's method of viscous constraint of the lap[8]. The length of the bar was originally 41 inches so as to span the gap over the grating carriage and thus to permit accurate finishing of the six supporting V's. Later, two 12-inch sections were cut from the bar and mounted coaxially in the supports. Each end of the carriage, which bridges the gap over the grating blank, is fitted with an inverted Graphitar V-block four inches long; the actual bearing areas on the round way are two strips about $\frac{3}{16}$ in. wide located on each side, 45° from the top of the way. These contact strips were finished by broaching on the grooved end of the original long bar. The advantages realized with this design are that each end of the carriage centers itself on the round way under gravity alone, oil films are self-equalized on each side, wear results only in an insignificant lowering of the diamond but not in a lateral displacement; and high precision is attained with far less labor than in finishing a flat-topped way. Furthermore, while wear of the Nitralloy under the lightly loaded Graphitar is very slow, the ways may be rotated after a few years to bring fresh portions of the steel surface into use. The diamond carriage is an aluminum-alloy casting weighing 13 pounds. The necessary reciprocating motion is transmitted to it from the cross head by a slightly resilient coupling link." [9]

A very important innovation in the mounting of the diamond was also introduced by BABCOCK and BABCOCK and described as follows (loc. cit. [9]).

Diamond mounting.

"Another modification of the diamond carriage, introduced some ten years ago, is in the manner of supporting the diamond. Long experience with pivot bearings of different types, for permitting the diamond to rule a groove on the pull stroke of the carriage and to be raised from the surface on the return stroke, showed that none of these was fully satisfactory. Either variations in pivot-bearing friction produced non-uniformities in the ruling, or a lack of definition in azimuth caused accidental errors. The pivots were finally discarded in favor of a support based on the Cardan hinge, or flat spring. The assembly is shown in Fig. ▮▮. Four short springs of 0.002-in. steel are used; two of these springs, crossed at 90°, support each end of the transverse horizontal rocking bar to which the diamond lever is attached. These springs allow the diamond only the one permissible degree of freedom, but in this there is good compliance, such that a ten-gram load will deflect the diamond about one mm. Much weaker springs might well suffice. As will be seen in the figure, the diamond in its shank is attached to the diamond lever by a clamp which permits adjustment for groove angle and for angle of attack. Low inertia of the rocking parts obviates any troublesome vibration during ruling. The whole diamond support is adjustable for elevation and for azimuth by means of micrometer screws. In setting up a grating blank on the machine, the plate is first levelled. Then the unloaded diamond is adjusted by the elevation micrometer to be just tangent to the surface. Finally the load is added to the upper part of the diamond shank. On the return stroke, after a groove has been ruled, the diamond is raised about one-half mm from the plate by a cam-actuated push-rod which descends on the opposite end of the diamond lever.

The performance of this diamond carriage has been satisfactory; our recent gratings made with six-inch grooves show virtually no local scattering, and high resolving power is now consistently achieved. Random and accidental errors have been practically eliminated." [9]

The new method of diamond mounting has found wide acceptance in ruling engines, especially for the ruling of plane gratings[1, 2, 13].

Some additional details on the ruling diamond, as used on the Mount Wilson engine are also given by BABCOCK and BABCOCK (loc. cit. [9]):

The ruling diamond.

"An earlier paper by one of us[22] of describes the development of the curved-edge diamond originated by ANDERSON and the design of gratings having a high concentration of light in chosen order, which is, of course, of particular importance in astronomical applications. Such gratings for the visual and photographic region of the spectrum are now often referred to as blazed gratings. It may be remarked that some of the very fine speculum gratings ruled by ANDERSON at Johns Hopkins University prior to 1910 have very good concentration of light in one order; these were produced with a natural diamond edge. Later, at the Mount Wilson Observatory, ANDERSON and JACOMINI constructed a machine in which two convex conical surfaces, having radii of the order of one inch, are cut and polished on the diamond. The intersection of these two surfaces is a sharp, curved edge, which in use is tangent to the surface of the blank. The metal is pressed to either side, leaving a smooth, burnished groove. For a typical stone the included angle is 105°, the angle of the "shallow" side is 15° from the horizontal, and the length of the edge is about one millimeter. In the final stages of finishing on the diamond lap, the edge must be examined frequently under a high power microscope with strong lateral illumination. Nicks in the edg may then be detected by their diffraction effects, they must be completely eliminated until the edge appears perfect. By changing the angle of attack of the stone, five or six different sections of the curved edge may be used in turn, each section ruling perhaps several gratings before the diamond needs refinishing. A good stone may be used almost indefinitely in this way. For groove angles of about 15°, we find that a load on the diamond of 15 to 20 grams is required if the spacing is 600 per millimeter, and 35 to 45 grams if the spacing is 400 per millimeter."

In might be noted in conclusion that it was this same Mount Wilson Observatory engine which was placed by H. W. BABCOCK under interferometric control in 1962[12] (see also Sect. 88.9), after HARRISON and STROKE[1, 2] had demonstrated in 1955 through 1961 the dramatic further improvements that could be attained over "built-in" mechanical "perfection" with the help of interferometric servo-control (see also Sects. 88.3, 88.4).

The performance of a 209 *mm* wide "*Babcock*" grating in a large 50 ft. vacuum spectrograph was determined with great care in 1956 by A. KEITH PIERCE[42]. Photographs of the hyperfine structure of the mercury line λ 5769 showed a resolution of 630000 in the 5th order. In the 11th order of Hg λ 2573,

[42] A. KEITH PIERCE: Performance of an Eight-Inch Babcock Grating in a large Vacuum Spectrograph. J. Opt. Soc. Amer. 47, 6–44 (1957).

the resolving power was estimated by PIERCE to be 1 200 000. The instrumental profile, the intensities of the satellite lines, and the ghost intensities were determined by photoelectric scanning of the green λ 5461 mercury line. The half-width of the "apparatus function" was found to be some 15% wider than the theoretical value.

The amplitude of the periodic error is somewhat difficult to estimate, inasmuch as the ghosts of the second order (G_2, Sect. 55) have 2, respectively 2.5 times the intensity G_1 of the ghosts of the first order. For a purely harmonic error, $G_2/G_1 \cong \frac{1}{4}$ (see Sect. 55), the first-order ghosts order being some 4 times more intense than the "second-order" ghosts. PIERCE (loc. cit. [42]) estimates the amplitude of the periodic error to be about 1/125 of the 17000 Å spacing, that is approximately 8×17 Å, which is representative of good mechanical engines.

Scattered light in the 5th order, after careful correction for the contribution by the wings of the lines, and ghosts, was estimated to be 0.7%. PIERCE notes that the scattered light remained approximately constant from order to order, and did "not appear to vary with the square of the order". As a result, PIERCE estimated the scattered light to be the non-dispersed scattered light in the spectrograph[42].

γ) *The interferometrically controlled M.I.T. engine.* γ1) General description. The principle of interferometric control of a continuously moving carriage, used successfully to rule 10-inch diffraction gratings on the M.I.T. ruling engine, was first described by HARRISON and STROKE (loc cit. [1]) in 1955 and is deceptively simple[19]. To rule a perfect grating, it is sufficient to make the instantaneous distance of the grating carriage from the start of the ruling be rigorously proportional to the accumulated "position" which the diamond tip has reached since the start of the first groove as it rules the grooves, always in the same "ruling plane", in a cyclic motion across the grating. The position of the diamond tip is measured by the accumulated angular position of the motor shaft that drives the diamond carriage and is taken as a reference. (Departures from linearity in the diamond velocity across the grating, along the groove length, can be simply corrected by mechanical means if necessary.) The instantaneous position of the grating carriage with respect to the start of the ruling is measured interferometrically with the help of an interferometer mirror rigidly attached to the grating carriage and moving with it, and the start of the ruling is materialized by another mirror and beam splitter which are maintained in a fixed position with respect to the "ruling plane". The grating carriage is made to advance at approximately the correct rate with the help of the ruling engine screw and an electromechanical gear system, connecting the diamond shaft to the screw through a differential. A grating-position control motor is also connected to this differential. If, as a result of mechanical imperfections in the engine and the screw, the grating carriage is incorrectly positioned by the direct drive, then the grating position error appears as an electrical signal. The error signal is produced by comparison of the instantaneous amplitude of the interferometric fringe signal (obtained from a photo-multiplier tube) and the instantaneous amplitude of the diamond-position reference signal (obtained from a signal-generator which is also geared into the diamond shaft). The grating position-error signal is made to rotate the servo-control motor in such a direction as to continuously and constantly maintain the grating in its correct position with respect to the start of the ruling and the diamond position by appropriately adding or subtracting to the carriage motion determined by the rotation of the engine screw, which is itself driven by the diamond shaft. A schematic diagram of the servo-control loop used in the control of the carriage translation on the M.I.T. ruling engine is shown in Fig. 140 and photographs of the engine in Fig. 141 and in Fig. 142. Details of the screw and of the diamond-carriage linearizing mechanism are shown in Fig. 143 and 144. A view of the engine, upon its arrival from Chicago in 1948, is shown in Fig. 145. It serves to show how much modification the M.I.T. engine has undergone (as described by HARRISON and STROKE) from its original Michelson Gale form (as attained bytot 1948). A view of the control room is shown in Fig. 146. Interferometric wave-front studies of gratings ruled on the M.I.T. ruling engine with this control scheme have demonstrated that grating imperfections could arise even on an interferometrically controlled engine, unless one also controlled any rotation, about a vertical axis passing through the translation-control mirror if necessary (that is when rotations result *from any curvature of the grating-carriage ways*). Moreover, ruling errors will arise in an interferometrically controlled engine if the grating plane (diamond tip) does not coincide with the center of gravity of the control-interferometer mirrors, in case of rotations (or "tips") about horizontal axis normal to the ruling direction. Finally, second-order ruling errors can also result, if unchecked, from a combination of interferometric and servo-control effects, as we show below. Moreover, since the groove spacing, under interferometric control, is determined by the wavelength of a light source in air, it is also necessary to either maintain constant atmospheric conditions during the course of the ruling, or to measure any atmospheric variations, to compute their effect on the ruling and to correct for them if they have occurred. HARRISON and STROKE[1,2] have found it preferable to use a simple analogue computer to correct for the effect of atmospheric variations, and in particular for the effect of pressure variations which have, by far, the largest effect.

The idea of controlling the ruling of gratings with the help of interferometers can certainly be traced all the way back to MICHELSON[43] who used interferometers and visual fringe settings to improve the quality of his ruling-engine screws. HARRISON (loc. cit.[23]) refers to W. W. HANSEN of Standard University as having undertaken work on interferometric control before his untimely death. Even a patent[44] on some of the obvious advantages of interferometric control of a ruling engine was granted in 1950, although without any mention of the crucial importance of the need for compensation for barometric changes of the wavelength, necessary for operation in air, etc. *More recently H. W. BABCOCK* (Sect. 88.9) has adopted interferometric control to the stop-and-go motion of the Mt. Wilson Laboratory engine in Pasadena, with pressure-correction similar to that used on the M.I.T. engine. However, rather than continuously correcting for errors as they occur (as is done on the M.I.T. engine), the error actually introduced into the grating on the n-th groove is corrected by shifting the following $(n+1)$-th groove in an attempt of minimizing cumulative and local errors. Since extended errors are more harmful to high-resolution gratings than residual local and periodic errors, it is probable that outstanding gratings will result with this method, on the Mt. Wilson engine, even though it does not aim at as complete a ruling control as that achieved in the method originated by HARRISON and STROKE in 1955[1] and subsequently expanded by HARRISON et al. in 1957[16],

[43] A. A. MICHELSON: Astrophys. J. 18, 278 (1903). — Nature 88, 362 (1912). — Studies in Optics. Chicago: Chicago University Press 1927, reprinted 1962, p. 86.

[44] R. F. STAMM: U.S. Patent 2527338 (Diffraction Grating Ruling Engine). Applied for Oct. 12, 1946, Granted Oct. 24, 1950.

STROKE (1957, 1958)[45], HARRISON (1958)[11], HARRISON et al. (196[illegible])[46], HARRISON and STROKE (1960)[47], STROKE (1961)[2].

It is known that both the Bausch and Lomb Company of Rochester, N.Y. and the Jarrell-Ash Company of Newtonville, Mass. have adopted the Harrison and Stroke scheme of interferometric control to engines in their ruling laboratories, and that other laboratories are preparing similar control. See following sections.

As a general order of magnitude, the good gratings obtained on the M.I.T. engine by 1961 were found (loc. cit.[2]) to be superior by factors of 100 to the famous gratings ruled by ROWLAND and ANDERSON at the beginning of this century, and in the early 1920's. Fig. 147 reproduces for comparison two low-angle (45°) wave-front interferograms, one of a plane grating ruled by J. A. ANDERSON in 1914 on speculum metal on ROWLAND's engine, and considered as very good at that time, and the other of an early grating ruled under interferometric control on the M.I.T. ruling engine. It is apparent from the discussion in Sects. 20, 51 to 59 that ROWLAND's gratings were considered to be so good at their time because they were meant to be used only at very low angles, up to 10° or so in autocollimation, where the wavefronts were some 4 times better and the spectral quality of the gratings some 16 times better than here at 45°.

How much care needs to be exerted in comparing grating performance, with only the help of resolution photographs or hyperfine structure (hfs) patterns as has been a practice in the past, becomes clear when the hfs of Fig. 148 is compared to the structures of Fig. 149. Unlike the patterns of Fig. 149 which were photographed with M.I.T. gratings 143 and 97 on a fast spectrographic plate 103 aF in only 30 sec, the hfs of Fig. 148 was obtained with the same first-generation grating 97 of Fig. 149 but now on a low-contrast, rather slow and considerably finer Panatomic-X film. An exposure of $1\frac{1}{2}$ min was required in Fig. 148 to attain a density comparable to the hfs of Fig. 149. A considerably better appearance of the hfs results under the conditions of Fig. 148 which, it is known, tend to conceal the existence of spurious satellites and weak ghosts and are usually impractical for spectrographic purposes: the hfs of grating 87 taken on the finegrain film of Fig. 148 would in fact erroneously tend to favor this grating when compared to the hfs of grating 143 taken on the coarsegrain plate in Fig. 149. For the purpose of working comparison, the hfs patterns of Fig. 149 were obtained with both gratings under normal spectrographic conditions (in fact the hfs of the two gratings were actually photographed on the same plate and with the same exposure, in an attempt to bring out the component a with the most similar density possible (which was almost achieved on the plate). It is quite apparent from Fig. 149 that a group of satellite lines described by s appears in the use of grating 97 with a density very similar to the density of component a: the satellites s result in a broadening of the lines from grating 97 when compared to the new grating 143 (where no such satellites appear and where the resolution is noticeably better under identical conditions). The wave-front interferograms of Fig. 149 are not subject to any such photographic effects: their power in grating assessment and engine improvements has now been established and clearly appears from the comparisons.

[45] G. W. STROKE: Photoelectric fringe signal information and range in interferometers with moving mirrors. J. Opt. Soc. Amer. **47**, 1097–1103 (1957); **48**, 276 (1958).

[46] G. R. HARRISON, N. STURGIS, S. P. DAVIS, and Y. YAMADA: J. Opt. Soc. Amer. **49**, 205–211 (1959).

[47] G. R. HARRISON, and G. W. STROKE: J. Opt. Soc. Amer. **50**, 1153–1158 (1960).

That the quality of the M.I.T. gratings is indeed being attained as a result of interferometric control is illustrated by the low angle (16°) interferogram of Fig. 150 when compared with ANDERSON's grating of Fig. 147, it is seen that without control the M.I.T. engine does not produce an acceptable grating even for use at the lowest possible angles around 5°, while the controlled engine is capable of producing the outstanding grating of Fig. 149.

The engine control-conditions which have resulted in the ruling of high-resolution gratings of the quality of grating 143 are briefly described below. Experience has shown that their systematic use will indeed combine to result in the attainment of outstanding, flat, high-resolution gratings when ruled under *interferometric control*.

First, it is in order to give some background concerning the origin of this engine[10].

The basic mechanical parts of *the 14-inch ruling engine were constructed under* the direction of A. A. MICHELSON in 1900 at the University of Chicago. The engine was modified there in the 1930's by H. G. GALE, F. PEARSON, T. J. O'DONNELL and others, and in 1948, it was presented to G. R. HARRISON at M.I.T. in a form about two-thirds finished. As described by HARRISON, STROKE and associates, this engine has since been completed, modified further and put under interferometric control. As aearly as 1956, a number of excellent plane gratings up to 8-inches in ruled-width had been obtained[10], under simultaneous interferometric control of both translation and rotation. Further improvements, resulting from refinements in interferometer adjustments and increased stability, eventually resulted in the outstanding gratings described by HARRISON and STROKE *in 1960 and 1961*[17, 2].

γ2) Some details of the control system. Only some of the less obvious details of the interferometric control system are given here. Additional details are found in the original papers. Most of the techniques described are being found useful in laser interferometry and machine-tool control.

Adjustments of interferometers for grating-ruling control. Uncalled-for corrections might be introduced by the photoelectric servo-mechanism into the ruling engine if the interferometer-mirror motion results in an instantaneous flux distribution across the mirror aperture which does not properly represent the grating position. Errors can result in particular from improper location of the center of gravity of the interferometer-mirrors with respect to the grating plane.

An equal-inclination ring fringe-system obtained from flat mirrors is used for the interferometric control of the moving grating-blank carriage on the M.I.T. ruling engine as shown in Fig. 151. The green 5461-Å line is obtained from a Meggers Hg 198 tube excited in an electrodeless discharge at about 200 Mc/sec and cooled by a moderately strong air current at about 70° F[48]. Only small portion of the central part of the ring system is isolated by a circular diaphragm (source hole) placed in the focal plane of the collimator lens. The flux transmitted through the interferometer, and modulated as a result of the motion of the moving mirror, at the rate of 1 fringe cycle for every $\frac{1}{2}\lambda$ of carriage advance, is focused onto a 931-A photomultiplier tube. A representative fringe signal obtained on the M.I.T. engine is shown in Fig. 152. It is important that the source hole be accurately centered on the common normal to the moving and reference mirrors, which is also the center of the ring system in the focal plane of the collimator. The diameter of the rings decreases with the mirror separation according to well-known

[48] W. F. MEGGERS and F. O. WESTFALL, J. Res. Nat. Bur. Stand. 44, 447 (1950).

laws, and a source-hole aperture of 1 mm diameter (in the focal plane of the 1 m collimator) is chosen as so to correspond to only a small fraction of the central fringe at the maximum mirror separation of 5 inches used in the ruling of 10-inch gratings. It is essential not only to center the hole by autocollimation on the mirrors, but to center it actually on the ring system. Although this was pointed out in the original paper by HARRISON and STROKE[1] (1955) dealing with the principle of the interferometric control used on the M.I.T. engine, experience has shown that some additional clarification to what is meant by "interferometric" centering may be desirable (STROKE 1961)[2]. An eccentricity of only 1 mm in the focal plane of the 1 m collimator will indeed result in the additional count of an entire fringe on either extreme of a 10-inch grating, which may be sufficient to account for the curvature of some of the 10-inch gratings previously described.

The source hole can be easily centered by first setting the interferometer to some small mirror separation of, say, 20 to 40 mm. After bringing the two source-hole images into coincidence in the usual manner, the straight-line fringe system located in the vicinity of the mirrors can be observed with the help of a low-power telescope. When the interferometer mirrors have been made as parallel as possible by spreading out the fringes, a very clearly visible ring fringe-system will be observable in the plane of the extended Hg 198 tube if the telescope has been refocused on the source hole, and the source hole then removed. If the telescope cross hair is brought to coincide with the center of the ring system, and the source hole is replaced into its position in front of the Hg 198 tube, it can be easily moved until its image coincides with the cross hair of the undisturbed telescope. An adjustment within 0.1 mm in the source plane (corresponding to about 1/10 fringe of grating flatness) is easily achieved.

Any local change in fringe-signal amplitude will be interpreted by the servo-control as a translation error of the control-mirror involved. If the amplitude change is caused by a local mirror-parallelism variation, an uncalled-for correction may result and an error might be introduced into a grating at a place where it was properly positioned by the fringe field. The rotation control about an axis normal to the grating plane and to the direction of grating advance helps in suppressing effects resulting from rotations about vertical axes. But rotations about a horizontal axis parallel to the gratings plane and normal to the direction of grating advance will result in both a simple geometrical ruling error (when the interferometer mirror aperture is not centered on the grating plane) and in a more subtle error caused by a combination of interferometric and servo-mechanical origins. The geometrical error can be simply taken care of by centering the interferometer mirror aperture on the ruling plane within the tolerances of the order of 1 mm, as appears from Fig. [redacted]. The fringe-signal amplitude variations across the mirror aperture which result from rotations about the horizontal axes — and which attend the use of a plane mirrors — may, however, still lead to ruling errors unless their effect is also rendered negligible. The fringe-signal amplitude referred to here is that by which one usually describes the amplitude of the periodic signal: it is not the instantaneous value of the fringe-signal (which does, however, depend on the amplitude, or course). Local errors up to $\frac{1}{2}$ fringe would result in the gratings ruled on the M.I.T. ruling engine before the new corrections were carried out by STROKE (1961)[2] (Fig. 153 to 154). The effect discussed here had also been predicted on theoretical grounds (STROKE 1957), and it was shown that it increases with the number (or fractional number) of fringes in the interferometer aperture (for imperfectly parallel mirrros), or alternately with the size of the aperture in presence of the number of fringes in the aperture. The new improvement consisted simply in masking down the vertical height of the interferometer aperture to about 10 mm or less. It remains, of course, essential to locate the center of gravity of the interferometer aperture slit on the plane of the ruling.

One might note, in conclusion, that the mirror location problem is somewhat different in interferometric spectrometers [MICHELSON (1927)[49], FELLGETT (1951, 1958)[50], JACQUINOT (1954, 1958, 1960)[51], CONNES (1960, 1961)[52]]: there the *motion* of interest is that of the mirror or the corner-cube itself, and it is sufficient that its own position be correctly measured and controlled. In the controlled ruling of gratings, the interferometric element is generally placed at some considerable distance from the groove that is being ruled: it is the difference in translational components between the grating and the interferometers which tends to result in ruling errors if permitted to remain uncorrected. It is in fact the problem of correctly positioning the grating over its entire traverse when moving over rather imperfect ways which has made it so difficult to attain high-resolution gratings, even with interferometric control.

Rotation control. Trasnlation control alone, in the direction of blank advance, has been found to be insufficient on the M.I.T. ruling engine, as a result of the various rotations caused by the balls on which the blank-carriage rolls in the course of its advance, and as a result of the curvature of the cylindrical ways which guide the balls [HARRISON, STURGIS, BAKER and STROKE (1957)]. More classical ruling engine ways, such as the "doublevee" ways already used by ROWLAND, may also cause rotation problems, in particular as a result of lubrication irregularities.

With the help of an alignment interferometer, the ways can be easily and rapidly adjusted to an average straightness of ± 1 fringe (measured across a 10-inch interferometer arm) over the 10-inch traverse *in a horizontal plane* (STROKE 1961)[53]. A sketch of the alignment interferometer, according to STROKE[53], is shown in Fig. 155.

In the ruling engine, the local parallelism of the grating advance continues to be maintained with the help of an interferometric servo-mechanism identical to one used in the translation-control loop (*Fig.* 140) by comparing the fringe signals obtained from two regions of the same mirror placed some 4-inches apart, as illustrated in Fig. 156. One of these mirror regions is located exactly above a preloaded ball-bearing pivot and the entire grating table is rotated by the interferometric rotation-control servomechanism about a vertical axis defined by the ball bearing and passing through the *front* of the translation mirror. The translation control results in accurate positioning of the grating-carriage within about $\pm 1/100$ fringe (about $\pm 0.003\ \mu$ or $\pm 10^{-7}$ inch) over the 10-inch traverse, and in maintaining the parallelism to $\pm 1/200$ sec of arc.

A general view of the M.I.T. ruling engine is shown in Fig. 141 and a close-up of the control-interferometers in Fig. 142. A view of the control room is shown in Fig. 146.

[49] A. A. MICHELSON: Studies in Optics. Chicago. Chicago University Press 1927, reprinted 1962.

[50] P. FELLGETT: Thesis Cambridge University (Cambridge England, 1951). J. Phys. Radium **19**, 187, 237 (1958).

[51] P. JACQUINOT: XVIIe Congr. du G.A.M.S. (Paris 1954). J. Phys. Radium **19**, 223 (1958). — Rep. Progr. Phys. **23**, 267 (1960).

[52] J. CONNES: Rev. d'Opt. **40**, 45, 116, 171, 231 (1961).

[53] G. W. STROKE: An alignment interferometer for precision straightness measurements and control, even of rapidly moving carriages. J. Opt. Soc. Amer. **51**, 1340–1341 (1961).

Correction for the effects on the interferometric control system of barometric changes of wavelength. Under *interferometric control*, the groove position and spacing are determined by the wavelength of the radiation (for instance the green Hg 198 radiation) in air. The wavelength in air changes with variation barometric pressure, temperature, water vapor and CO_2 partial pressure as well as with the introduction of any foreign gasses or vapors (BARRELL and SEARS 1939)[54]. In practice, when the temperature is controlled to the tolerances of 1/100° C or better as required by the mechanical elements of the ruling engine, variations in barometric pressure produce the major change of wavelength, according to an equation

$$\Delta m = 3.31\, \Delta P\, \Delta L$$

where Δm is the fringe shift in 1/100 fringe ($\frac{1}{2}\lambda$), ΔP is the pressure variation in inches of mercury, ΔL is the mirror separation from zero path difference in mm. For example, if a pressure change of $\Delta P = 1/3.3$ inches should occur when the grating is at $\Delta L = 100$ mm from zero path difference, then the grating would be shifted by $\Delta m \approx 100$ hundredths of a fringe, or approximately by one fringe by the controlling servo-mechanisms, a very larger error indeed, if it remained uncorrected. In reality the pressure change does not only result in a shift of the grating at the time when a pressure change occurs, but it also produces further errors as a result of a spacing in the now incorrect wavelength (as compared to the wavelength at the pressure P_0 at the start of ruling). Finally, the sign of the grating shift changes when the grating interferometer mirror passes through zero path difference. When the grating moves toward zero path difference, a pressure increase (which decreases the wavelength and tends to pull the grating towards zero path difference) moves the grating "forward" in the direction of its motion. However, the pull towards zero path difference will move the grating backwards from its direction of motion when the grating moves away from zero path difference. The grating shifts, both "instantaneous" (at the time of the pressure change) and "cumulative" (as a result of the changed wavelength) result from the operation of the servo-control phase detecting system, which is designed to continuously synchronize the interferometric fringe signal with the diamond-position reference signal. The phase detecting system only knows about fringes and their position relative to the reference, but it ignores the differences in the origin of fringe shifts (real position error or change of wavelength). It is the *function of the analogue computing cam* shown in Fig. 146, to help in calculating the instantaneous uncalled-for grating shifts, and to accordingly shift the reference signal generator, *relatively to the diamond-shaft, in order to maintain* the correct grating position relative to the start of ruling and the diamond. The height of the two-dimensional hyperbolic cam materializes, with the help of appropriate linear slopes, the variations of fringe-shift as a function of path difference and pressure change in the range of operation. The pointer which rides on the cam is directly geared into a differential placed between the diamond-shaft and the diamond-position reference signal generator. The computing can also be carried out with the help of an electronic multiplication circuit using "helipot" resistors and a servo-motor to feed the differential[12, 55].

Recent indications are that pressure compensation in control interferometers is more directly achievable by suitably controlling the frequency of a gaseous

[54] H. BARRELL and J. E. SEARS: Phil. Trans. Roy. Soc. Lond. A **238**, 1 (1939).

[55] R. F. JARRELL and G. W. STROKE: New advances in grating ruling, replication and testing. Appl. Optics ■■. ■■■ (1964).

optical maser[56]. The description of an optical phase discriminator appears to have been given for the first time in this report[56].

The temperature control used on M.I.T. ruling engine is described in Sect. 87.

Diamond-carriage control. The interferometric control of the grating-carriage advance implies that the diamond carriage moves in the ruling plane parallel to the fixed reference mirror within a few hundredths of a fringe (some 0.01 μ) during the course of some 15 miles of equivalent traverse, which correspond to the ruling of a 10-inch grating at 300 grooves/mm. The design of the grating carriage used on the M.I.T. ruling engine was described by HARRISON and STROKE (1955)[1], and it has successfully withstood the test of time in maintaining the diamond in the ruling plane within better than 1/15 fringe. This result is of course not achieved without careful adjustment of the mechanical elements involved. The diamond carriage is suspended from two bearings riding on a monorail, which is fixed on the engine, and rests with a plastic (Rulon) shoe on a long optical flat, which is also fixed on the engine in a position at right angles to the grating motion. It is the long flat which determines the ruling plane. So far it has not been found necessary to use interferometric control of the diamond with respect to its reference mirror or indeed to a reference mirror at the beginning of the grating, but further improvements in grating quality may result from the use of a servo-system for that purpose, as well as from possible interferometric monitoring of the reference-mirror position itself with respect to the beam-splitting tower and other fixed interferometer components, in particular: the use of the extremely sharp spectral lines produced by optical masers [SCHAWLOW and TOWNES (1958)[57], JAVAN (1960)[58], JAVAN et al. (1961)[59]] should prove invaluable in interferometric control.

A schematic view of the diamond carriage, and of the diamond bearing hinges, according to HARRISON and STROKE[1] is shown in Fig. 157 and an interferometric record of the diamond-carriage position in Fig. 158.

δ) *The interferometrically controlled Jarrell-Ash Engine.* A greatly simplified version of the Harrison and Stroke principle of controlled ruling of diffraction gratings with a continuously moving carriage has now been successfully developed and applied by G. W. STROKE to a good mechanical 10-inch engine built by WM. MACARTHUR and D. K. RICE at the Jarrell-Ash Company[13].

The work on the interferometric control system for the Jarrell-Ash engine was carried out by G. W. STROKE with WM. MACARTHUR and JOHN BERNIER, and a more complete description of this engine and of its control features is given by R. F. JARRELL and G. W. STROKE [13b] together with additional details concerning grating ruling and replication methods developed at Jarrell-Ash for the production of high-resolution gratings[55]. Over half a dozen good gratings up to 6-inches in width and with spacings up to 30000 lines per inch have already been successfully ruled with the new control system.

A block diagram of the Jarrell-Ash engine and of its interferometric control system are shown in Fig. 159 and a photograph of the complete engine in Fig. 160. Fig. 161 shows an enlarged view of the gear train used in driving the grating carriage approximately in synchronism with the diamond carriage, at a rate of

[56] G. W. STROKE: In: Frequency control stability, and interactions between modes in gas lasers (unpublished) — Perkin-Elmer Engineering Report No. M 7287 A (May 27, 1963).

[57] A. L. SCHAWLOW and C. H. TOWNES: Rev. 112, 1940 (1958).

[58] A. JAVAN: In: Quantum Electronics, ed. by C. H. TOWNES, p. 564. New York: Columbia Un. Press 1960.

[59] A. JAVAN, W. R. BENNETT and D. R. HERRIOTT: Phys. Rev. Letters 6, 106 (1961).

about eleven grooves per minute. The Hg 198 light source, photoelectric tubes and electronics are located outside of the engine case. One of the remarkable features of this control system is that the gears which are taking the motion off the main shaft are directly placed on the engine. With specially ground gears in this group as well as in the gear train, and with careful alignment, no vibrations at all have been found to enter the engine, the ruling diamond or the interferometers.

Fig. 162 shows the interference fringe signal produced by the advance of the grating carriage on the Jarrell-Ash engine and the remarkable degree of control achieved in the closed-loop operation during the course of controlled ruling of a 30000 lines per inch grating: an instant of time has been chosen when an error of about $1/10^6$ inches (1/10 fringe) with respect to the diamond carriage reference signal was being corrected, as achieved in the right half of the oscilloscope photograph. A wavefront interferogram of an early 6-inch 30000 lines per inch grating is shown in Fig. 163, with the last half inch showing a portion of ruling produced without control for comparison. About 12 days are required to rule a 6-inch 30000 lines per inch grating, during the course of which the diamond carriage must be maintained in the same ruling plane to better than 10 inches during a 10-mile reciprocating traverse, the temperature must be maintained to a few 10° C, and the grating carriage must be brought to its appropriate position also to better than 10 inches at every instant of time with the help of the interferometric servo-control.

It is noteworthy, for the new Jarrell-Ash engine control, that it was found possible to successfully use a teflon worm to drive the large worm gear (Fig. 161): no sign of wear has appeared in many months of continuous operation. The variations in wavelength and the corresponding errors which would result from the variations in atmospheric pressure during the course of the ruling are being corrected by a simple electronic computer according to the principle previously described (HARRISON and STROKE 1955, STROKE 1961).

In addition to ruling gratings with adequately flat wavefronts, perhaps the most remarkable feature on the introduction of the interferometric servo control system on the Jarrell-Ash engine is the dramatic reduction in the intensity of Rowland ghosts, which result from periodic errors in the ruling. The best mechanical engines usually present Rowland ghost intensities on the order of 1/2000 in the first order of a 15000 lines per inch grating in the visible. The very first grating ruled under control on the Jarrell-Ash engine, and every grating since, has had the ghost intensity reduced from the usual 1/2000 to much less than 1/100000, doing apparently better even than M.I.T. engine, and showing the advantages of continuous motion control used on both these engines, as well as on the smaller Bausch and Lomb engines, compared to what seems to be achievable under stop and go motion. No disadvantages of any kind have been observed to result from ruling with continuous grating carriage motion. In particular, no need was found for linearizing the diamond carriage motion, thus adding to the simplicity of the control system[13, 55].

e) The Bausch & Lomb Michelson Engine, and B & L interferometrically controlled engines. The large ruling engine now at BAUSCH and LOMB was one of the two engines built at the University of Chicago shortly after the turn of the 20th century and remained there under the direction of Professor GALE until 1948. It was presented to BAUSCH and LOMB at that time, while its sister engine was presented to M.I.T.

As described by BAUSCH and LOMB in 1957, "The size of the engine is such that it could rule gratings with grooves over 150 mm in length and a width of ruling up to 300 mm. However, it will require several additional years of work on the engine to achieve this size of useful ruled area. The present maximum is 153 × 203 mm.

The mechanism for advancing the grating carriage was designed for great flexibility. This makes it possible to rule gratings with a wide choice of numbers of grooves or grating spacings per mm. Since the precision screw has a 2 mm lead, grating spacings are given as number of grooves per mm. Useful gratings are ruled in ranges from 20 grooves pre mm to 1080 mm.

The precision screw (Fig. 164), which is the heart of any ruling engine has been studied with great care to learn the nature of its errors. Even though the screw is very good, the remaining errors are sufficient to produce substantial Rowland ghosts, unless corrected. An electronic fringe counting system, using the wavelength of the green light from Hg 180 isotope as the standard of length, is employed to plot the error curve for the screw. This curve supplies the data necessary for cutting a brass cam that supplies the exact correction needed to minimize the Rowland shosts."

The measurement system used to produce the correction cams, is quite similar to the system described by HARRISON and ARCHER[30]. It was described by FINKELSTEIN, BRUMLEY and MELTZER[60] in 1952 with particular reference to the correction of periodic errors:

"The interferometric error recorder, Fig. 165, plots on a revolving drum the lead or lag of the grating blank carriage relative to its theoretically correct position as a function of distance along the screw. The unit of measurement is an interference fringe, half a wavelength of the 5461 A green line emitted by a high frequency discharge tube containing the 198 isotope of mercury. The error curve thus recorded was separated into its component harmonics by a numerical Fourier analysis, and from the information obtained concerning the periodicities present and their amplitudes, it was possible to calculate the expected ghost intensities. Finally, a corrector cam was cut.

The selsyn generator, shown in Fig. 165 is rotated continuously by the gearhead motor, drives two followers. The first follower drives the grating ruling engine screw at a speed of approximately one turn every fifteen minutes. The second follower drives a drum covered with recording paper at exactly 540 times that speed. As the grating carriage moves along the screw, carrying one mirror of a Michelson interferometer, the interference fringes move across the face of the diaphragm, *D*, causing the light falling on the photomultiplier to vary, reaching one maximum and one minimum for each half wavelength motion of the grating carriage. The signal from the anode of the photomultiplier is amplified, clipped, and differentiated to produce pulses which trigger the electronic counter. The counter is set to close a switch for an instant when the count has reached 217. This actuates a plunger on the recorder which punches a small hole in the recording paper.

Fig. 166 shows an error recorder plot for two turns of the screw both before and after the corrector cam was inserted. The up direction corresponds to the grating blank carriage lagging behind its correct position along the screw, and the down direction corresponds to the carriage leading the screw. The peak-to-peak spread of the uncorrected curve is about 500 angstroms. The curves shown are not the ones taken directly from the recorder, but are different only in that the background noise has been removed. A twenty-four point numerical Fourier analysis was performed on these curves to calculate all periodicities which are harmonics of the pitch of the screw."

The measured amplitude of the harmonic component of the periodic error achieved after correction was of the order of 4.5×17 Å, being perhaps 1.5 times smaller than mechanically non-corrected errors on other good mechanical engines, but about 5 times larger than the errors obtained on the interferometrically controlled engines with continuous carriage motion.

A general view of the Bausch and Lomb engine is given in Fig. 167 and a detail of the diamond carriage in Fig. 168. A very considerable number of good ratings up to 8-in wide have been successfully ruled on this engine. A sketch of the underground laboratory in which the engine is located is given in Fig. 169. Many additional details about this engine, in particular its applications to the ruling of accurate scales, are given by RICHARDSON and STARK[61].

[60] N. A. FINKELSTEIN, C. H. BRUMLEY and R. J. MELTZER: J. Opt. Soc. Amer. 42, 121—126 (1952).

[61] D. RICHARDSON, and R. M. STARK: J. Opt. Soc. Amer. 47, 1—5 (1957).

A small four-inch engine, built in part by DAVID MANN, was brought under interferometric control at M.I.T., and subsequently transferred to BAUSCH and LOMB around 1960, and another similar engine (Fig. 170 and 171) was brought under interferometric control at BAUSCH and LOMB. The design principles and general performance of these engines were described in 1963 by E. LOEWEN*, and a block diagram of the control system is shown in Fig. [redacted]. The system is quite similar to the control system first described by HARRISON and STROKE[1].

Much of the mechanical work on the Bausch and Lomb engines, and the ruling of gratings, has been carried out under the supervision of ROBERT WILEY[60, 61]. The contributions made by BAUSCH and LOMB to supplying fine spectroscopic gratings and replicas has been singularly outstanding. The role held in these achievements by DAVID RICHARDSON has been particularly recognized.

ζ) *The Baird-Atomic infrared grating engines.* In a private communication[62], these engines are described by WALTER BAIRD as follows:

"We have built two ruling engines. The first was started about 1941 or 1942 and moved ahead very slowly through the war years. As I remember, we first began ruling gratings in 1946 and I think I can say with reasonable accuracy that this was the first successful ruling engine bulit by an industrial firm, although I may be wrong.

The basic engine is very similar to the ROWLAND as modified by ANDERSON and WOOD and of course Wilbur Perry. In other words, it was a double cross slide with a 20-thread to the inch screw and 750 teeth on the dividing head. We did do several things differently from the Hopkins approach. First, we wished to get rid of the change from static to dynamic friction and arranged our drive so that the engine was moving the blank as the diamond was cutting. This was done by two mechanical devices-one, a set of elliptical gears which were arranged so that the diamond carriage and therefore the diamond was cutting the blank at the slow period of the elliptical gears while the return permitted the blank to advance very rapidly, never coming to a complete stop. The second innovation was the driving of the screw instead as on the Hopkins instrument with a ratched and pawl arrangement, with a worm advancing with a worm wheel. Now this, while getting rid of static friction, should produce ruled lines that have theoretically an "S" shaped contour, but to my knowledge, we have never been able to show that this affected resolving power.

Most of our rulings have been on 4 inch diameter blanks, almost all 3 meter radius of curvature. While we tried other surfaces than aluminum for experimenting, aluminum has been the standard.

This engine ruled successfully for about twelve years and only until the period about 1955 were we ever greatly concerned if the first order Rowland ghosts were less than 1/500.

In 1948, we got started on another engine which is very similar to the first. A few small innovations were made largely to permit the disengagement of the worm wheel drive of the screw from the scerw itself and to take care of corrections. This engine has been ruling fairly steadily for the last five years and early we introduced one further innovation, and I think again we were the first to try it, and that was to put 1/1000th inch strips of Teflon on the ways as an antifriction material. This engine is still ruling excellent gratings.

We have had in the last two years Frank Cooke re do the first Engine and I must say he has done a beautiful job. We had one unfortunate happening in the last six months, just as this engine was beginning to go to work again. A sprinkler head let go in the night and dowsed the engine completely with very rusty dirty water. It was some hours before this accident was discovered and as a consequence, a fair amount of pitting, particularly on the lead screw, took place. This is now being relapped. We expect it back again shortly.

Almost all of our gratings have been 4-inch diameter, 3 meter, 15000 lines to the inch. We have changed blaze angle, depending upon the requirement. In general, all of the gratings have been used as high as the 4th order. We have ruled gratings at 7500, 5000 lines to the inch, for special purposes. At one time, just to prove we could do it, we did rule a 6 inch grating. For our spectrographs, our gratings were expected to work from far ultraviolet, 1000 angstroms out as far as one micron."

The Baird Atomic grating ruling project was started upon the initiative of WALTER BAIRD, and significant early contributions to it were made by WM.

[62] W. BAIRD: Private communication to G. W. STROKE (March 28, 1962).

* E. G. LOEWEN: Positioning system spaces lines to within 1/10 microinch. Control Engineering 10, 95—97 (1963).

LANGTON[62]. Most of the construction, making the nut, lapping the screw was carried out by FRANK GILLIS[62]. Appreciable advice appears to have been received from JOHNS HOPKINS, in particular from WILBUR PERRY[62].

Caps.

η) *The state optical institute engine.* The principle features of this engine and the performance of the gratings ruled were described in 1958 by GERASIMOV et al.[24].

"The most notable point about this machine lies in the design of the two basic mechanisms: A double carriage is used in the first, as proposed by STONE[63] and used by GALE[64] when adapting one of MICHELSON'S engines. The carriage is in two parts placed one above the other (Fig. 173). The lower part is driven along the guide 2 by the screws; the friction between guide and carriage is large and variable in time, so this movement is not of high precision. The upper part 4 carries the blank 5 and is joined to the lower by the four flat spring 6, which allow the two parts to move relative to one another along the feed direction only. The second part is moved by the screw 7, of the same pitch as the first screw. The forces acting on the second screw arise from internal friction in the springs, and are almost constant if the two screws are synchronously driven, this ensures high accuracy in the feed. The two worm drives to the two screws (4a and 4b in Fig. 174) are identical and are driven from the same drive. Ten teeth are in mesh at once on the gears, which eliminates local irregularities in the teeth.

It has been found by interference methods that a force of 5 g wt applied to the upper part displaces the carriage elastically by about 0.01 μ, which approaches the maximum permissible error in ruling. The working force on the screw is in fact constant to 2–3 g wt. The upper part follows strictly the law prescribed by the drive mechanism, whereas the lower does not, because of the friction in the ways."

Hydrodynamic friction principles are used in the ways of the ruling mechanism, so wear of the surfaces is virtually eliminated, even though up to 180000 movements are required for a large grating. The ruling carriage consists of a rigid girder which works on ways and is driven by a crank mechanism; the ruling instrument is carried at the centre. Separate guides are used for controlling the horizontal and vertical motions, as shown in Fig. 173b, because the forces acting and the accuracies required in these two directions differ. The horizontal supports are three-self-leveling shoes 1 which slide on flat polished surfaces 2 immersed in the oil baths 3. The rubbing surfaces of the shoes are spherical (radius of curvature about 1 km), this gives a stable motion and a continuously formed fairly thick oil film between the rubbing surfaces, so the friction is hydrodynamic.

The vertical guides are formed by two flat glass blocks 4 fixed to the base at the ends of the carriage on opposite sides. Spherical lignum vitae supports rest on the block and are tensioned by sprung levers. No lubricant is used. The forces required to move the carriage are very low, and the motion is smooth and highly rectilinear.

The machine is set up on an antivibration base in a constant-temperature enclosure."

Plane and concave gratings of all usual types are being ruled on this engine, up to areas of 150 × 150 mm, and spacings of 1200, 600, 300 and 200 lines/mm.

The best gratings show resolving powers of 600000 and the Rowland ghost intensity in the 1st order of a 600 lines/mm grating was usually found to be 0.1 %, corresponding to a periodic error amplitude of 10 × 17 Å. In some very good gratings, Rowland ghost intensities as low as 0.01 % were observed (corresponding approximately to 3 × 17 Å periodic error amplitude).

The gratings are tested with the help of the interferometric wave-front testing method first described by STROKE in 1955[65], although the method is ascribed by GERASIMOV et al. (loc. cit.[24]) to GERASIMOV et al.[66], (1957).

Very careful measurements were carried out by GERASIMOV et al. (loc. cit.[24]) on all the important aspects of grating performance. Scttered light was found to be less than 10^{-5}. The work by these authors on intensity distribution and

[63] W. STONE. J. Sci. Instrum. **11**, 241 (1934).

[64] H. G. GALE. J. Sci. Instrum. **12**, 32 (1935).

[65] G. W. STROKE. Interferometric measurement of wave-front aberrations in gratings and echelles. J. Opt. Soc. Amer. **45**, 30–35 (1955).

[66] F. M. GERASIMOV, E. A. TEL'IEVSKII, S. N. SPIZHARSKII and S. V. NESMELOV: Optiko-mekh. Prom. No. 4, 56 (1957).

polarization is particularly notable, not only because they have obtained remarkably high efficiencies with 110° to 120° diamonds, but also because, just like R. W. WOOD[67,68] in 1910, they speculate, incorrectly (as since shown by STROKE[69], see also Sect. 62) that "The reflection coefficient could be increased considerably by reducing the angle between the faces to 90°, ..."[24]. As shown by STROKE (loc. cit.[69] and Sect. 26), the 90° angle is precisely one of the most undesirable angles, when high efficiencies are sought, because of its tendency towards polarizing the diffracted light; and consequently toward *reducing* the efficiency in gratings; 110° and 120° angles are those recommended[69]. One may conclude, therefore, that the use of 110° and 120° angles by GERASIMOV et al., as by R. W. WOOD, was fortuitous rather than deliberate, even though the quality of their gratings has apparently greatly benefited from this angle. As described by GERASIMOV et al.[24]:

"Intensity distribution and polarization. The best gratings, with line faces inclined at 5–10°, throw up to 85% of the reflected light in a single maximum; this is quite close to the theoretical value. Practically all the light is reflected by the broad faces (Fig. 175); if the inclination of these faces is increased the fraction of the incident beam which strikes these working faces, and hence the efficiency with which the light is used gradually falls because the angle between the two faces is 110–120°. The reflection coefficient at the maximum does not exceed 55% if the inclination is raised to 40°. The reflection coefficient could be increased considerably by reducing the angle between the faces to 90°, but the difficulties of making good diamond points for the purpose have prevented this method from being used. Data have been given on the mean and maximum reflection coefficients of gratings in various orders[66, 70].

Fig. 176 shows typical intensity curves (in arbitrary units) for the blaze region of a grating with 600 lines/mm which concentrates the light into the first order visible region centered on 5400 Å. The measurements were made on a photoelectric autocollimation apparatus using the brightest lines from cadmium, mercury and potassium. The reflection intensities were recorded relative to those found with an *aluminized mirror* at the same wavelengths. Curve 1 was taken in polarized light, the other two curves were taken with the electric vector of the polarized light normal (2) and parallel (3) to the lines. The thick line indicates the theoretical *intensity distribution*; the experimental results fall only fairly near the theoretical curve. A notable feature is that the state of polarization changes as the maximum is passed through; the component with its electric vector parallel to the lines is the stronger on the short-wave side, and the other on the other side. The same effect is found with blazed gratings with 1200, 600, 300 and 200 lines/mm. Fig. 177 shows $\varrho_{\perp}/\varrho_{\parallel}$ values (accurate to ±3%), for 5 gratings, the blaze maxima are indicated by vertical lines (accurate to 200–300 Å). The change in the predominant sense of polarization occurs at the blaze peak, within the error of measurement. The various gratings differ considerably in their degrees of polarization; the shapes *of the* reflecting surfaces in the lines are responsible.

Gratings ruled on aluminum, whether blazed or not, show anomalies in their intensity distributions similar to those first *found* by WOOD[71]; *fairly* narrow dark bands which vary in spectral position with the angle of incidence are seen in continuous spectra. This effect is seen only when the electric vector is normal to the lines* with rulings of 1200 and 600 *lines/mm*; many gratings do not reflect at all with in these bands. RAYLEIGH[17] has shown that the anomalies always lie at wavelengths such that the waves are diffracted along the surface of the grating, these wavelengths λ are given by

$$a(1 \pm \sin i) = m\lambda$$

where a is the grating constant, i is the angle of incidence and m is the order of the spectrum.

[67] R. W. WOOD: Phil. Mag. **20**, 770 (1910).

[68] A. TROWBRIDGE and R. W. WOOD: Phil. Mag. **20**, 886 (1910).

[69] G. W. STROKE: Attainment of high efficiencies in blazed gratings by avoiding polarization in the diffracted light. Phys. Letters **5**, 45–48 (1963).

[70] F. M. GERASIMOV: Izv. Akad. Nauk. SSSR Ser. fiz. **6**, 662 (1954).

[71] R. W. WOOD: Proc. Phys. Soc. Lond. **18**, 396 (1902).

* C. H. PALMER, Diffraction anomalies with a dielectric grating [J. Opt. Soc. Amer. **54**, 844 (1964)], shows "anomalies" for both the P and the S polarizations. See also Sects. 60 to 71.

Our gratings in general give anomalies in accordance with this formula, but the bands differ considerably in width and intensity, even with otherwise identical gratings. The anomalies cause dips on the intensity distribution curves for certain gratings (cf. Figs. 176 and 177); calculation shows that the anomalies lie at 4800 and 6700 Å for the 600 lines/mm grating used in the 1st order in the autocollimation apparatus. The dips in Figs. 176 and 177 for the first anomaly actually lie at somewhat longer wavelengths. The anomalies at 6700 Å are readily seen by eye using continuous spectra these gratings, they have not been studied in detail. Some gratings show only very weak anomalies near the blaze; the precise relation of this effect to the ruling technique has not yet been established. The anomalies accour with both senses of polarization with gratings of 300 and 200 lines/mm, but are stronger when the electric vector is normal to the lines."

It is noted that GERASIMOV et al.[24] use electron-microscopy for the testing of the groove profiles of the gratings ruled at the State Optical Institute.

One of the largest State Optical Institute gratings described is a 150 mm wide, 600 line/mm grating, used in the spectrograph with the large telescope at the Crimean Observatory[24] and showing a resolving power of 600000 in the 7th order ($N = 600 \times 150 = 90000$, $m = 7$ giving a theoretical resolving power $Nm = 630000$). Another smaller grating (ruled width 100 mm, 600 lines/mm) is at the Potsdam Observatory, where it was tested by SCHRÖTTER[72], the resolving power was found to have the theoretical value of 360000.

GERASIMOV et al.[24] find that "on average, gratings of high constants give better images than ones of low constants" with gratings ruled on their machine.

η) The Perkin-Elmer engines. The Perkin-Elmer ruling engines were first designed and constructed at the Applied Research Laboratories by JULIUS PEARSON with the assistance of GUS M. GOMEZ, who now is in charge of the engines at the Perkin-Elmer Laboratory in California. An overall view of one of the engines is shown in Fig. 178. Infrared gratings up to inches have successfully ruled since about 1961, and the entire grating ruling and testing program is under the direction of H. W. MARSHALL. Interferometric wave-front testing is used, as well as grating efficiency testing in a double-monochromator arrangement (see Sect. 77). The grating replication methods now in general use are based to an important extent on work carried out at the Perkin-Elmer Corporation by Fraser and White during the middle 1940's (see Sect. 89).

θ) The Mount Wilson Observatory engine with interferometric control. The Mount Wilson Laboratory engine, described in Sect. 88, was put under interferometric servo-control, and described in 1962 by H. W. BABCOCK[12], following the succesful demonstration of interferometric control of ruling engines by HARRISON and STROKE in 1955 to 1961[1,2].

Intermittent, stop and go, motion and control are used by BABCOCK and several new features associated with the use of a "modulated" Michelson Twyman Green interferometer are described in his 1962 paper.

The interferometer is modulated by deflecting the compensating plate electromechanically, so as to simultaneously permit a small 60 cps oscillation of the fringe pattern, as well as compensation for barometric pressure-change effects on the wavelength (Fig. 179).

The oscillating fringe pattern is scanned by a phototube and is reproduced on a monitoring cathode-ray tube. Any decentering of the pn-th fringe on the n-th groove (p = number of fringes per groove) is detected by synchronous demodulation and is converted to a stored electrical charge. The correction for any error

[72] E. H. SCHRÖTTER, Phys. Verh. 6, 143 (1957).

on the n-th groove is applied to the following $(n+1)$-th groove, by introducing into the mechanism a differential correction proportional to the stored charge. Clearly, perfection in the correction would appear to assume that the error to be corrected on the $(n+1)$-th groove will end by being substantially equal to the error on the n-th groove from which the correction has been determined. This is quite different from the continuous-control Harrison and Stroke principle[1,2], where no long-distance anticipating error assumptions are made, and perfection appears achievable within the time-constant of the servo-system, corresponding to an infinitesimal fraction of a groove-spacing. Comparison of gratings ruled under these rather different conditions would be most revealing. No detailed results of grating wave-front tests, ghost-intensity or spectroscopic performance of the gratings ruled under the new interferometric control system are given in the original paper[13]. BABCOCK states (loc. cit. [13]):

"The 25-cm ruling engine with interferometric control has proved to be reliable in operation and in the past few months has produced several gratings of high quality in sizes up to 13 × 20 cm. These are blazed plane gratings ruled on aluminized blanks that are flat to one-fortieth wavelength. There is no bar to the employment of the control system for larger gratings up to the limit set by the dimensions of the machine. It may be emphasized again, however, that several characteristics, in addition to adequate precision in spacing of the grooves must be combined in any really satisfactory grating, especially if it is to be used in spectrophotometry of absorption lines arising in faint astronomical sources."

Some of the details of the control system as described by BABCOCK are given in what follows:

"The Mount Wilson Observatory engine has been successfully operated in a purely mechanical mode for many years, has a demonstrated capacity in the production of gratings up to 15 × 25 cm. Tests of the performance of one of these gratings have been described by PIERCE[12]. The addition of interferometric control was undertaken with the double aim of still further reducing residual errors of spacing and of minimizing the nonproductive time spent in critical adjustments of mechanical parts.

In order to ensure straightness of the grooves, to avoid extensive mechanical alterations to the machine, to achieve maximum simplicity, and to permit operating either with or without interferometric control, it was decided to retain intermittent advance of the grating carriage, together with simple, crank-driven, reciprocating motion of the ruling diamond. By appropriate choice of the spur gears used in the intermittent drive for the worm that advances the 900-tooth gear and the main screw, it is a simple matter to advance the grating carriage an integral number of fringes in each spacing operation. The spacing most in demand is approximately 600 grooves per millimeter, or 15000 per inch. If gearing is chosen to make the spacing 610.3 grooves per millimeter, the grating constant will be three wavelengths of green mercury light (λ 5460.7531); thus almost exactly six fringes will pass in the field of the interferometer for each spacing cycle.

The control system employs an electrooptic 'fringe clamp' device. After each incremental advance of the grating carriage, while the diamond is ruling a groove, a phototube senses any deviation from exact centering of the stationary tenth fringe. The resulting electrical error signal is stored, and during the next spacing operation it is converted to a shaft rotation which, after a large reduction through gearing, is introduced as a differential correction into the spacing mechanism of the machine. In the present instance, the differential correction is applied through a rotation of the screw-mounted end-thrust bearing of the worm that advances the main spacing gear (Fig. 179).

The modulated interferometer. The interferometer is of the Michelson type, with the moving mirror carried on one end of the grating carriage. The beam splitter, fixed mirror, and compensating plate are mounted on a substantial bench attached to the base of the machine. The source, a water-cooled Meggers Hg 198 isotope lamp excited at 2500 Mc/s, together with its collimating lens, is mounted outside the enclosure that houses the ruling engine. An interference filter isolates the green line. Light emergent from the interferometer is focused by a projection lens to form a system of concentric rings on a screen, also outside the enclosure. A small aperture in the center of the screen admits light from the center of the fringe pattern to a 10-stage electron-multiplier phototube. The radius of the aperture is only a fraction of the width of the narrowest fringes, which occur for maximum path difference. To provide for on the n-th groove is applied to the following $(n+1)$-th groove, by introducing into the mechanism a differential correction proportional to the stored charge. Clearly, perfection in the correction would appear to assume that the error to be corrected on the $(n+1)$-th groove will end by being substantially equal to the error on the n-th groove from which the correction has been determined. This is quite different from the continuous-control Harrison and Stroke principle[1,2], where no long-distance anticipating error assumptions are made, and perfection appears achievable within the time-constant of the servo-system, corresponding to an infinitesimal fraction of a groove-spacing. Comparison of gratings ruled under these rather different conditions would be most *revealing*. No detailed results of grating wave-front tests, ghost-intensity or spectroscopic performance of the gratings ruled under the new interferometric control system are given in the original paper[13]. BABCOCK states (loc. cit. [13]):

"The 25-cm ruling engine with interferometric control has proved to be reliable in opera-
tion and in the past few months has produced several gratings of high quality in sizes up to
13 × 20 cm. These are blazed plane gratings ruled on aluminized blanks that are flat to one-
fortieth wavelength. There is no bar to the employment of the control system for larger
gratings up to the limit set by the dimensions of the machine. It may be emphasized again,
however, that several characteristics, in addition to adequate precision in spacing of the grooves
must be combined in any really satisfactory grating, especially if it is to be used in spectro-
photometry of absorption lines arising in faint astronomical sources."

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mechanical mode for many years, has a demonstrated capacity in the production of gratings
up to 15 × 25 cm. Tests of the performance of one of these gratings have been described by
PIERCE[12]. The addition of interferometric control was undertaken with the double aim of still
further reducing residual errors of spacing and of minimizing the nonproductive time spent
in critical adjustments of mechanical parts.

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to the machine, to achieve maximum simplicity, and to permit operating either with or
without interferometric control, it was decided to retain intermittent advance of the grating
carriage, together with simple, crank-driven, reciprocating motion of the ruling diamond.
By appropriate choice of the spur gears used in the intermittent drive the for worm that
advances the 600-tooth gear and the main screw, it is a simple matter to advance the grating
carriage an integral number of fringes in each spacing operation. The spacing most in demand
is approximately 600 grooves per millimeter, or 15000 per inch. If gearing is chosen to make
the spacing 610.3 grooves per millimeter, the grating constant will be three wavelengths of
green mercury light (λ 5460.7531); thus almost exactly six fringes will pass in the field of the
interferometer for each spacing cycle.

The control system employs an electrooptic 'fringe clamp' device. After each incremental
advance of the grating carriage, while the diamond is ruling a groove, a phototube senses any
deviation from exact centering of the stationary 6nth fringe. The resulting electrical error
signal is stored, and during the next spacing operation it is converted to a shaft rotation
which, after a large reduction through gearing, is introduced as a differential correction into
the spacing mechanism of the machine. In the present instance, the differential correction is
applied through a rotation of the screw-mounted end-thrust bearing of the worm that advances
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the moving mirror carried on one end of the grating carriage. The beam splitter, fixed mirror,
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interference filter isolates the green line. Light emergent from the interferometer is focused by
a projection lens to form a system of concentric rings on a screen, also outside the enclosure.
A small aperture in the center of the screen admits light from the center of the fringe pattern
to a 10-stage electron-multiplier phototube. The radius of the aperture is only a fraction of the
width of the narrowest fringes, which occur for maximum path difference. To provide for

sensitive detection of the position of the 6nth fringe, which is just appearing or disappearing at the center of the concentric pattern, as well as to compensate for changes in barometric pressure, the interferometer is modulated.

Modulation is accomplished by giving a slight angular displacement to the tilted compensating plate of the interferometer, which is supported on a flat steel spring, or Cardan hinge. The voice coil and magnet from a loudspeaker are so mounted (the voice coil being attached to the plate holder) that a small alternating current applied to the coil provides an angular vibration of the compensating plate, such that the optical fringe pattern sweeps back and forth with an adjustable range at a frequency of 60 cps. At the same time, a direct current applied to the same coil from a simple analog computer deflects the plate in order to compensate for changes in barometric pressure.

Fringe clamp circuit. With the interferometer modulated at 60 cps, the amplified output of the phototube is conveniently applied to the vertical deflecting plates of a monitoring oscilloscope while a 60 cps sine wave is applied to the horizontal plates. The resulting trace reproduces the portion of the fringe system that is being scanned. If the amplitude of modulation is sufficient, two or more complete fringes can easily be displayed, although in actual operation the amplitude is set at about 1/5 fringe. If a dark fringe is centered on the aperture, the scanning will result in a U-shaped pattern appearing on the oscilloscope. Any slight decentering of the fringe will cause the U to become asymmetric. For control purposes the phototube signal is further amplified and then demodulated by a balanced synchronous rectifier. Any error in the centering of the 6nth fringe results in a proportional imbalance in the charge developed on the capacitors C and [illegible]. At the conclusion of the scan phase, which occupies about 40% of each cycle, the error correcting motor (Fig. 179) is caused to turn in the direction and by an amount determined by the stored signal. Switching of the signal circuit and of the correcting motor at the appropriate phases is accomplished through mercury switches operated by cams on the main crankshaft of the ruling engine.

When the machine is operating under interferometric control, the clamping of the fringes is readily monitored by observation of the oscilloscope, which also displays the intermittent advance of the fringe pattern during the spacing part of each cycle. An indication of error amplitude is also given by a sensitive voltmeter connected across C and [illegible].

Feedback for error correction. Error correction appears in the form of intermittent rotation of the shaft of a small reversible motor. After passing through a miniature variable-speed transmission and further gear reducers, the shaft rotation is introduced as a differential correction into the spacing mechanism of the ruling engine. The mechanical differential for this purpose might take any one of several forms, in the present case the simplest method was to control the position of the end thrust bearing of the spacing worm that advances the 600-tooth gear on the main screw. The end-thrust bearing is mounted on a fine-pitch screw that is rotated by the correcting motor. The range of longitudinal travel of the worm is 25 mm corresponding to an accumulated correction of some 100 fringes in the ruling of a single grating. The intermittent driving device, which rotates the worm through spur gears, is a cylindrical cam that is given exactly one turn for each spacing operation. A 1:1 spur gear ratio yields a spacing of 600 grooves per millimeter. It was found by trial ruling under interferometric control that multiplying the grating space by the factor 0.983151 would, at a temperature of 23.9° C and at a fixed barometric pressure, result in a cumulative correction of zero for a large ruling. This factor was closely approximated by spur gears for driving the worm in the ratio 117:119 or 0.983193.

By providing additional sets of spur gears in appropriate ratios, or otherwise altering the mechanical spacing, it is readily possible to rule under interferometric control at other grating constants corresponding to integral numbers of fringes other than six."

Details on the pressure computing system, similar to those used by HARRISON and STROKE[1,2,13] are also given by BABCOCK[12], together with details on the diamond carriage and on the theoretical capabilities expected from the control system.

i) The Jobin et Yvon interferometrically controlled engine. A 4-inch mechanical ruling engine, using novel friction reducing principles and pneumatically assisted movements was completed by R. GOULLEY under the direction of G. PIEUCHARD at JOBIN et YVON by 1959. At that time experiments on further mechanical improvements of this engine and on testing the grating performance were undertaken with the help of G. W. STROKE. These experiments eventually led to the recommendation for designing an interferometric control system, following the successful principles demonstrated by HARRISON and STROKE[1,2]. The stop-and-go interferometric control system of a very simple and novel design was completed by P. CONNES, G. PIEUCHARD and R. GOULLEY by 1962/63.

A general view of the engine is shown in Fig. 180a and a schematic diagram of the control system in Fig. 180b.

The part of G. W. STROKE in helping to initiate the French grating ruling program is briefly described in the May 1962 "International Optics" issue of Applied Optics.[72].

Gratings of good quality with 600 lines/mm and 75 mm width were obtained as early as 1964, and the ruling of larger grating under interferometric control is now under way. The Jobin et Yvon engine is capable of ruling gratings of 100 × 70 mm. The number of fringes passing through the interferometer is determined before the carriage is locked: as result periodic errors are eliminated. Random spacing errors are minimized by a compensating coil which controls the fine motion of the carriage during the ruling of the groove. The compensating coil is excited by the difference signal obtained from the two photomultipliers used in the double-interferometer system (one near the source hole, the other at the exit hole [*]).

ϰ) *The CSIRO Australian engine.* A general view of the engine as developed by D. A. DAVIES and G. STIFF is given in Fig. 181a and 181b and some details, according to a (1962) description by DAVIES[74] are given in what follows:

"The engine has a nominal capacity of 4 inch length of line by 6-inch ruled width for spacings of 32400, 16200 and 10800 lines per inch. (Sizes $4\frac{1}{2}$-inch × $6\frac{1}{2}$-inch with 16200 lines per inch have been ruled). At present only plane gratings can be ruled, but it is intended to add the extra equipment for ruling concave gratings at a later date and a simple modification to allow coarser pitches to be ruled. Preliminary measurements indicate that gratings of six-inch ruled width with 100000 lines when measured in the first order at 5400 Å may have Rowland ghost intensities less than 1/10000th of the parent line, efficiencies relative to a plane aluminized surface of 75%, and wavefront errors better than 1/5th wavelength."

The engine is housed inside of a temperature-controlled cabinet and works at a ruling rate of 19 strokes per minute.

As described by DAVIES (loc. cit. [74]),

"Most of the engined and constructed by the Division of Chemical Physics at FISHERMEN'S Bend, Melbourne. As shown in Fig. [redacted] the reciprocating "shaper" arm (upper left) slides to and fro on two cylindrical precision-lapped guides fixed in line. The central portion of the arm bridges between the guides and beneath it is attached the diamond carriage above the work table which in operation is slowly fed through the gap. To restrain the arm from rotation on the guides, a projection from it bears on a flat strip showing at the rear centre of the picture.

The work table is supported on a parallel pair of cylindrical guides visible across the centre of the photo. The feed screw is located (parallel) between them, and is rotated by the large gearwheel (at right), outside the bearing. Between the bearing and the work table is the long precision nut whose motion is transmitted to the table by connecting bars.

In the bottom right corner can be seen portion of a spur pinion on the worm spindle which drives the feed gearwheel. This drive is interconnected with equipment behind the partition in the background, through which projects the driven end of the reciprocating arm."

At present, DAVIES and STIFF are considering a new design of engine specifically for use with servo-control[75].

[72] G. AMAT, A. ARSAC, J. BROCHARD, J. BROSSEL, P. CONNES, L. COUTURE, P. JACQUINOT and A. MARECHAL: Les Reseaux Optiques. In: Optics in France. Appl. Optics 1, 209—278 (1962), p. 262.

[*] G. PIEUCHARD: Private communication (1964).

[74] D. A. DAVIES: The C.S.I.R.O. Ruling Engine. In: Diffraction Gratings, pp. 101–108. J. Astronom. Soc. Victoria 15, 101—108 (1962).

[75] D. A. DAVIS: Private communication to G. W. STROKE, Feb. 18, (1964).

λ) *The University of Tokyo engine.* The ruling engine of the Institute for Optical Research, Kyôiku University Tokyo is shown in Fig. 182.1, and a diagram according to the 1952 paper by FUJIOKA, SAKAYANAGI and KITAYAMA[76] is shown in Fig. 182.2. The ruling engine is being used for ruling infrared gratings of 360 lines/mm and 40 lines/mm with an area of 100 mm × 70 mm*. Fairly extensive details on the history, construction, interferometric measurement of engine errors, and performance of the engine in its 1952 stage is given in the orginal paper[76]. The description of the interferometric measurement according to FUJIOKA, SAKAYANAGI and KITAYAMA (loc. cit.[76]) follows:

"To eliminate the errors of the ruling, we have first to measure and to correct them. For that purpose, we use a Michelson interferometer** which is shown schematically in Fig. 182.3. In that figure C means a plane mirror (29 of Fig. 182.2) which is fixed to the carrier of a grating, and A and B are two mirrors fixed to another plate which moves parallel to the grating carrier. If the image of $A(A')$ coincides with C, one can see nice interference fringes by using white light. In this case it is very easy to decide the position of the coincidence, because a slight in-coincidence causes a change of colour. Next we move C, until its coincidence with the image $B(B')$ is obtained, and the corresponding angle of rotation α_1 of the worm gear is read. We move next the carrier of A, B to obtain the coincidence of A' with C, and then C is moved until it coincides with B', the corresponding angle of rotation being α_2. The same process will be repeated.

If the screw is perfect and the rotation of it is very uniform, the angle α_1, α_2, etc. should always be coincident, actually they are not. Therefore we form the cylindrical cam to make α_1, α_2, etc. coincident. We took the distance of A and B about 1/9 mm and interpolated the intermediate part. The accuracy of the angle is 1/100 degree which corresponds to the 1/10 of the interference fringe. The error due to the excentricity of the worm gear plate, or that may be due to the incompleteness of the plate-and-ball contact, may have the period of one revolution. Such errors can be corrected by interpolation between 9 points in a revolution. However, if the teeth distance is so irregular that the accompanying errors have small periods within a revolution, nine points are not sufficient to observe them. In our instrument this seems to be just the case, and observations at smaller distances are desirable. In this case we have to observe so many points that the accuracy of the measurements must well be considered.

Our problems is just the same as in the case of measuring a long distance with a very short scale. Suppose we measure 1 mm by successive measurements of n times using a small scale of $1/n$ mm. If we denote the error of a single observation by Δ, the total probable error is $\sqrt{n}.\Delta$.

We consider the Rowland ghosts of a grating, namely the error having a period of one revolution of the main screw. The relative intensity of a Rowland ghost to the main line is given by***

$$G_l = \pi^2 m^2 \left(\frac{\varepsilon}{a}\right)^2$$

In this formula a means the grating constant, ε means an amplitude of the sinuous periodic error, and m means the order of the spectrum. We assume $\varepsilon = \sqrt{n}.\Delta$. The value of Δ is roughly $0.5/20\ \mu$, and thus for $n = 9$ we have $\sqrt{n}\,\Delta = 0.075\ \mu$. Putting $a = 1.8\ \mu$, we get for $m = 1$

$$G_l = \frac{4.3}{1000}.$$

The observed intensity of the Rowland ghost is however stronger than this value, and the intensity distribution is fairly deviated from ROWLAND's theory, and many ghosts of higher orders appear irregularly. For instance, the ghost of the 8th order is often very strong, as compared with those of younger orders.

From those circumstances we can conclude that the error is not so simple as of the period of one revolution, and there must be errors of still smaller periods. We have therefore to

[76] Y. FUJIOKA, Y. SAKAYANAGI and T. KITAYAMA: Endeavour of Grating Ruling in Japan. Science of Light 2, 1–7 (1952).

* P. MIYAKE: Private communication (1964).

** A. A. MICHELSON: J. Franklin Inst. 181, 785 (1916).

*** H. A. ROWLAND: Phil. Mag. 35, 397 (1893).

observe at more points than nine. In order to increase the accuracy, we used monochromatic light instead of white light. If we fix A and count the number of fringes, we can avoid the additive errors; but it is, of course, not easy to count some 4000 fringes/mm. However, as we have already corrected under a fraction of the wavelength using white light, we can fix a within the accuracy of one fringe. As we can read the fraction of a fringe accurately, we can determine the error of one revolution of the screw with the accuracy of A.

We used a mercury green line. Fig. 182 A shows an example of the measurement. This shows how much more complicated curve than that of a period of one revolution. Repeating such observations, we get the total correction for one revolution of the order of $\frac{1}{4}\,\lambda$ to $4\,\lambda$. The error of the long run is also corrected, first using white light and then using monochromatic light. In this case we used a cadmium red line instead of the mercury green line." (loc. cit.[78])

A new engine is under construction at the Institute for Optical Research in Tokyo, but no information is yet available.

μ) The Hitachi engine.

ν) The Merton NPL metrology-gratings engine. A novel approach to grating ruling was suggested in 1948 by Sir THOMAS MERTEN, before the introduction of interferometric servocontrol[1,2] in the hope of overcoming some of the mechanical difficulties associated with previous engines. In referring to Sir THOMAS MERTON, and his apparent criticism of ROWLAND's design; L. A. SAYCE[78] writes:

[Sir THOMAS MERTON] "... proposed that the grating be generated upon a cylinder, and cut as a very fine screw-thread by a continuous lathe-like action and that this helix should be 'opened out' upon a flat surface by a replica process. These suggestions were the starting point of a considerable programme of research at the National Physical Laboratory which has been going on for the past eight years. As so often happens, the problem which first seemed quite simple has proved to be a complex one and the principal difficulties have been those which we first dismissed as trivial. Our plan has been to overcome these difficulties by concentrating first upon relatively coarse rulings, for which there is considerable demand and, armed with this experience, to tackle the more formidable problems of producing the large gratings of very high resolution ..."

Even though it has become apparent that the gratings so produced so far did not appear to be of sufficient quality, for most low resolution infrared spectroscopy, in comparison with gratings readily obtained by ordinary mechanical engines, the gratings produced at NPL by the Merton process have proven to be of an unexpected and very great importance in the use of gratings for metrological purposes.

Some of the advantages of metrological gratings are discussed in Sect. 10. Extensive recent descriptions of the use of moirefringes obtained with gratings, in metrological applications are given by references [101] to [108] in Sect. 76.

Details of the NPL engine used to produce the primary helix for the Merton process are shown in Fig. 184, according to SAYCE[79].

A model of the "Merton-nut" device used for producing an improved "secondary" helix from the primary lathe-cut helix is shown in Fig. 185[79].

Interferograms (Fig. 186) of early gratings (first-order, 7500 lines/inch) obtained in a Fizeau interferometer show the important improvement obtained, as expected, by the use of the secondary helix[79].

ο) The Siegbahn Nobel Institute for Physics engines. Professor SIEGBAHN's engines have for long been the primary source of the world's most outstanding x-ray gratings. In fact, two engines are in successful operation at the Nobel In-

[78] L. A. SAYCE: The preparation and industrial applications of diffraction gratings. Trans. Soc. Instrum. Techn [illegible], 138—143 (1957).

[79] L. A. SAYCE: The production of diffraction gratings. Endeavour, (October 1953), pp. 210—216.

stitute for Physics in Stockholm, ruling not only x-ray gratings, but other gratings as well.

Two recent photographs of the larger engine are shown in Fig. 186.A1 and 186.A2 *.

A recent description by Professor MANNE SIEGBAHN of some of the characteristics of the large engine, as well as of a smaller engine, (the smaller one being used mostly for ruling of gratings for grazing incidence spectrometers follows). In reference to the larger engine (Fig. 186.A1 and 186.A2), Professor SIEGBAHN writes:

"This machine gives 1080 per/mm, or 540 respectively 360 if 2 respectively 3 cogs are passed for every ruled line. The carriage can be moved over a distance of 250 mm, which then corresponds to the maximum ruling width. This machine also has arrangements for ruling of gratings fro moiré purposes in exact millimeter scale with 250, 100 and 50 lines per/mm. The smaller ruling engine, mostly used for ruling of gratings for grazing incidence spectrometers is in some respects a simplified model with a maximum ruling width of 120 mm and a fundamental period giving 576 lines per/mm; with half cogs displacements it then gives 1152 lines per mm." (MANNE SIEGBAHN, loc. cit. *).

Additional references to the important earlier contributions to grating ruling made by SIEGBAHN and his associates are given in Sect. 82 (ref. 8), as well as in the 1949 paper by G. R. HARRISON (loc. cit. [22]).

π) *Further grating improvements.* New improvements in groove quality, important reductions in stray light and in scattered light in gratings, and indeed substantial improvement in grating quality and resolving power, especially at short wavelengths, and important increase in ruling speeds should result from full, three-dimensional interferometric servo-control of the ruling diamond itself. Work towards this goal is now under way at the University of Michigan, by STROKE, DENTON and MOHLER according to a method proposed by MOHLER and STROKE **.

89. Grating replication. The wide use of high-resolution gratings and grating spectrometers is due to a large part to the sucess in grating replication methods.

* MANNE SIEGBAHN. Private communication to G. W. STROKE (June 29, 1964).

** O. C. MOHLER and G. W. STROKE: Proposed method of attaining greatly improved large diffraction gratings by new principles of interferometric ruling engine control. Private communication to the U.S. National Aeronautics and Space Administration (October 1963).